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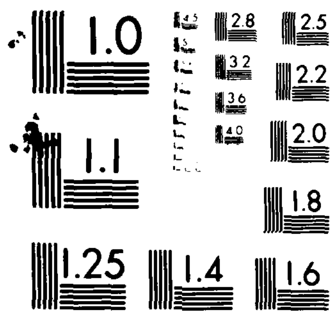

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IGNITION, COMBUSTION, DETONATION AND HEAT ADDITION TO ESTABLISHED FLOWS

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DEFLAGRATION, DETONATION, TRANSITION, INDUCTION DISTANCE, ENERGY TRANSFER, ITERATION, FLAME SPEED, LOW TEMPERATURE, DIFFUSER, COMBUSTION CHAMBER, EXHAUST NOSSLE, RAMJET, SPECIFIC THRUST, THRUST SPECIFIC FUEL CONSUMPTION, EQUILIBRIUM, SPEED OF SOUND, THERMODYNAMIC EFFICIENCY, OVERALL EFFICIENCY, ISENTROPIC, IRREVERSIBLE, CONSTANT AREA DUCT, NORMAL SHOCK WAVE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Detonation Induction distances have been measured at room-temperature at various initial pressures in hydrogen-oxygen third gas mixtures. Various detonation parameters of these mixtures have been calculated at various initial temperatures down to 100K. A conical burner tube with a wide approach section has been set up to measure the normal flame speeds of various hydrogen-oxygen third gas mixtures at temperatures down to 200K. A new combustion tube is being assembled for the study of heat addition to an existing flow of air.

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Rigorous calculations have been made to evaluate the performance of ramjets using hydrogen or propane as fuel and flying at speeds ranging from $M_\infty = 1$ to $M_\infty = 10$.

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*note: All Ramjet Data and Plots are for the subsonic combustion mode unless otherwise indicated

LIST OF SYMBOLS

A_c	cross sectional area of combustion chamber (m^2)
A_{DE}	cross sectional area of diffuser exit (m^2)
A_e	cross sectional area of exhaust nozzle exit (m^2)
A_f	cross sectional area of fuel injector exit (m^2)
A_i	cross sectional area of diffuser inlet (m^2)
Ar	chemical symbol for argon
$\left[a_{\ell j}\right]$	symmetrical matrix
$\left[b_{\ell j}\right]$	symmetrical matrix
C	chemical symbol for carbon
C_3H_8	chemical formula for propane
CO	chemical formula for carbon monoxide
CO_2	chemical formula for carbon dioxide
f	fuel to air mixture ratio
f_C	specified value of the ratio of the global mole number of carbon to the global mole number of' diatomic hydrogen in a fuel
f_{N_2}	specified value of the ratio of the global mole number of diatomic nitrogen to diatomic oxygen in an airflow (= 3.76)
$f_{N_2}^{calc}$	calculated value of f_{N_2}
f_{O_2}	specified value of the global mole number of diatomic oxygen to the global mole number of diatomic hydrogen in a combustion chamber
$f_{O_2}^{calc}$	calculated value of f_{O_2}
F_s	specific thrust ($N \cdot s/kg_{air}$) or (m/s)
F_{sfc}	thrust specific fuel consumption (kg_{fuel}/hour N)

LIST OF SYMBOLS (continued)

f_{N_2/O_2}	specified value of the ratio of the global mole number of diatomic nitrogen to the global mole number of diatomic oxygen in a combustion chamber
$f^{calc}_{N_2/O_2}$	calculated value of f_{N_2/O_2}
g	constant used in combustion chamber pressure calculation
He	chemical symbol for helium
$\left(\frac{H-E_0}{\mathcal{R}T}\right)_i^T$	reduced sensible enthalpy of specie i at temperature T
$\left(\frac{H_f^o}{\mathcal{R}}\right)_i$	absolute formation enthalpy of specie i at 0 degrees Kelvin (K)
$\left(\frac{h_f}{\mathcal{R}}\right)_{eq\ air}^{T_\infty}$	enthalpy of equilibrium air at T_∞^o (K kmol/kg)
$\left(\frac{h_f}{\mathcal{R}}\right)_{eq\ air}^{T_{DE}^o}$	enthalpy of equilibrium air at T_{DE}^o (K kmol/kg)
$\left(\frac{h_f}{\mathcal{R}}\right)_{eq.\ air}^{T_{DE}}$	enthalpy of equilibrium air at T_{DE} (K kmol/kg)
$\left(\frac{h_f}{\mathcal{R}}\right)_{air}^{T_\infty}$	enthalpy of normal air at T_∞ (K kmol/kg)
$\left(\frac{h_f}{\mathcal{R}}\right)_{eq\ air}^{T_{DE}^o\ CALC}$	calculated enthalpy of equilibrium air at T_{DE}^o (K kmol/kg)
$\left(\frac{h_f}{\mathcal{R}}\right)_{eq.\ air}^{T_{DE}^{CALC}}$	calculated enthalpy of equilibrium air at T_{DE} (K kmol/kg)

LIST OF SYMBOLS (continued)

H	chemical symbol for monatomic hydrogen
H_2	chemical symbol for diatomic hydrogen
H_2O	chemical formula for water
K^{CO_2}	equilibrium constant for CO_2
K^{H}	equilibrium constant for H
K^{H_2O}	equilibrium constant for water
K^{N}	equilibrium constant for N
K^{NO}	equilibrium constant for NO
K^{OH}	equilibrium constant for OH
K^{O}	equilibrium constant for O
$\mathcal{M}_1$	molecular mass of unburned gas mixture in a combustion tube (kg/kmol)
$\mathcal{M}_{CG}$	molecular mass of a combustion gas (kg/kmol)
$\mathcal{M}_c$	molecular mass of carbon (12.01115 kg/kmol)
$\mathcal{M}_{H_2}$	molecular mass of hydrogen (2.01594 kg/kmol)
$\mathcal{M}_{N_2}$	molecular mass of nitrogen (28.0134 kg/kmol)
$\mathcal{M}_{O_2}$	molecular mass of oxygen (31.9988 kg/kmol)
$\mathcal{M}_{air}$	molecular mass of normal air (28.85067 kg/kmol)
$\mathcal{M}_{DE}$	molecular mass of equilibrium air at a diffuser exit (kg/kmol)
$\mathcal{M}_e$	molecular mass of exhaust gas at a nozzle exit (kg/kmol)
M_∞, M_F	freestream Mach number
$M_{DE}, {}^{s}M_{DE}$	Mach number and specified Mach number at a diffuser exit

M_c	combustion chamber exit Mach number
N	chemical symbol for monatomic nitrogen
N_2	chemical symbol for diatomic nitrogen
NO	chemical formula for nitric oxide
O	chemical symbol for monatomic oxygen
O_2	chemical symbol for diatomic oxygen
OH	chemical symbol for OH
p_1	pressure of unburned gas mixture in a combustion tube (atm.)
p_3	pressure of combusted gases behind a detonation wave (atm.)
p_∞	freestream pressure (atm.)
p^o_∞	freestream stagnation pressure (atm.)
p_{DE}	diffuser exit pressure (atm.)
p^o_{DE}	diffuser exit stagnation pressure (atm.)
p_e	exhaust nozzle exit pressure (atm.)
p_c	combustion chamber pressure (atm.)
$p_i^{N.S.}$	pressure of airflow behind a normal shock wave at a diffuser inlet (atm.)
$p_i^{N.S.^o}$	stagnation pressure of airflow behind a normal shock wave at a diffuser inlet (atm.)
$p_i^{(M-C)}$	pressure behind a normal shock wave at a diffuser inlet according to the <u>m</u>omentum and <u>c</u>ontinuity equations (atm.)
$p_i^{(St-C)}$	pressure behind a normal shock wave at a diffuser inlet according to the equation of <u>st</u>ate and <u>c</u>ontinuity (atm.)

$\mathcal{R}$	universal gas constant (8314.33 J/kmol K)
$\mathcal{R}^*$	universal gas constant (.082056057 m^3 atm./kmol K = /(101325 N/m^2 atm.))
$\left(\frac{s}{\mathcal{R}}\right)_{eq\,air}^{T_{DE}}$	entropy of equilibrium air at T_{DE} (kmol/kg)
$\left(\frac{s}{\mathcal{R}}\right)_{air}^{T_\infty}$	entropy of normal air at T_∞ (kmol/kg)
$\left(\frac{s}{\mathcal{R}}\right)_{eq.\,air}^{T_i^{N.S.}}$	entropy of equilibrium air behind a normal shock wave at diffuser inlet (kmol/kg)
$\left(\frac{s}{\mathcal{R}}\right)_{CG}^{T_C}$	entropy of combustion gas at T_c (kmol/kg)
$\left(\frac{s}{\mathcal{R}}\right)_{CG}^{T_e}$	entropy of exhaust gas at nozzle exit (kmol/kg)
$\left(\frac{\Delta s}{\mathcal{R}}\right)$	entropy increment (kmol/kg)
T_1	temperature of unburned gas mixture in a combustion tube (K)
T_3	temperature of combusted gases behind a detonation wave (K)
T_∞	freestream temperature (K)
T_∞^o	freestream stagnation temperature (K)
$T_i^{N.S.}$	airflow temperature behind a normal shock wave at a diffuser inlet (K)
$T_i^{oN.S.}$	airflow stagnation temperature behind a normal shock wave at a diffuser inlet (K)

LIST OF SYMBOLS (continued)

T_{DE}	temperature at diffuser exit (K)
T^o_{DE}	stagnation temperature at diffuser exit (K)
T_c	combustion chamber temperature (K)
T_e	exhaust nozzle exit temperature (K)
T^o_c	combustion chamber stagnation temperature (K)
u_∞	freestream velocity (m/s)
u_{DE}, ${}^s u_{DE}$	diffuser exit velocity and specified diffuser exit velocity (m/s)
$u_{DE}^{(M-C)}$	diffuser exit velocity calculated from combination of momentum and continuity equations (m/s)
$u_{DE}^{(St-C)}$	diffuser exit velocity calculated from combination of equation of state and continuity equation (m/s)
$u_i^{N.S.}$	velocity of airflow behind a normal shock wave at a diffuser inlet (m/s)
u_c	velocity at combustion chamber exit (m/s)
u_e	velocity at exhaust nozzle exit (m/s)
u_3	difference between detonation wave velocities w_1 and w_3 (m/s)
v_3/v_1	ratio of specific volumes of unburned (1) to burned (3) gases in a detonation process
$w_{a,3}$	speed of sound in burned gases behind a detonation wave (m/s)
$w_{a,\infty}$	speed of sound in freestream (m/s)
w_1	velocity of a detonation wave with respect to the unburned gas mixture ahead of it (m/s)
w_3	velocity of the tail of a detonation wave with respect to the burned gases behind it (m/s)

$\left(\frac{C_p}{\mathcal{R}}\right)_i^T$	dimensionless specific heat of specie i at temperature T
$a_i^{T_L}$	coefficient of equilibrium constant for specie i at temperature T_L
η_{th}	thermodynamic efficiency
η_p	propulsive efficiency
η_o	overall efficiency
η_{CO}	mole fraction for CO
η_{CO_2}	mole fraction for CO_2
η_C^g	global mole fraction of carbon
η_H	mole fraction of H
η_{H_2}	mole fraction of H_2
$\eta_{H_2}^g$	global mole fraction of diatomic hydrogen
η_N	mole fraction of N
η_{N_2}	mole fraction of N_2
$\eta_{N_2}^g$	global mole fraction of diatomic nitrogen
η_O	mole fraction of O
η_{O_2}	mole fraction of O_2
$\eta_{O_2}^g$	global mole fraction of diatomic oxygen

LIST OF SYMBOLS (continued)

η_{H_2O}	mole fraction of water
η_{OH}	mole fraction of OH
ν_C^g	global mole number of carbon in fuel
$\nu_{H_2}^g$	global mole number of diatomic hydrogen in fuel
$\nu_{N_2}^g$	global mole number of diatomic nitrogen
$\nu_{O_2}^g$	global mole number of diatomic oxygen
$\gamma_{CG\ eff}^{T_3}$	effective ratio of specific heats in combustion gas behind a detonation wave
γ_F	frozen ratio of specific heats in a combustion gas
T_f	fuel injection temperature (K)
u_f	fuel injection speed (m/s)
ρ_f	fuel density (kg/m^3)
$h_{comb,fuel}^{T_f}$	heat of combustion of fuel at T_f (J/kg) (H_2: -119×10^6 J/kg ; C_3H_8: -46×10^6 J/kg)
$(c_s)_i^T$	entropy coefficient of specie i at temperature T $= \left[\frac{(\frac{S}{\mathcal{R}})}{\ln T}\right]_i^T$

$|n|$ absolute value of n

Linear Interpolation Symbols

T_L	100·(integer part of (T/100)) for tables listing thermodynamic functions at 100 degree temperature intervals (K)
$\Delta a_i^{T_L}$	$a_i^{(T_L+100)} - a_i^{T_L}$
$\Delta\left(\frac{H-E_o}{\mathcal{R}T}\right)_i^{T_L}$	$\left(\frac{H-E_o}{\mathcal{R}T}\right)_i^{(T_L+100)} - \left(\frac{H-E_o}{\mathcal{R}T}\right)_i^{T_L}$
$\Delta(c_s)_i^{T_L}$	$(c_s)_i^{(T_L+100)} - (c_s)_i^{T_L}$
$\Delta\left(\frac{C_p}{\mathcal{R}}\right)_i^{T_L}$	$\left(\frac{C_p}{\mathcal{R}}\right)_i^{(T_L+100)} - \left(\frac{C_p}{\mathcal{R}}\right)_i^{T_L}$

note: all symbols without units listed are dimensionless

IGNITION, COMBUSTION, DETONATION AND

HEAT ADDITION TO ESTABLISHED FLOWS

These different phases of this research effort have been investigated and partially completed during this reporting period from the first of April 1979 through the 30th of April 1981.

I. TRANSITION FROM DEFLAGRATION TO DETONATION

A. INTRODUCTION

Because of difficulties encountered with the available instrumentation in the experiments at very low initial temperature, measurements were first made at room temperature (approximately 300 K) and calculations were made of the energy transfer to the detonated gas for various H_2-O_2-Third Gas mixtures. In the meantime, the low temperature equipment has been improved so that these experiments can be continued.

B. Detonation of gas mixtures containing Hydrogen, Oxygen and either Carbon Dioxide, Nitrogen, Helium or Argon as a third component.

1. Experimental Results

Experiments have continued in the investigation of the effect of initial pressure on the detonation induction distance of a combustible gas mixture containing Hydrogen and Oxygen as as the primary constituents. Previous experiments have shown that as initial pressure increases, the detonation induction distance decreases. The results presented in this report are in agreement with these earlier observations. All experiments were performed while maintaining the gas mixtures at room temperature (approximately 300 K) prior to ignition. Before presentation of the data, a description of the apparatus and the experimental procedure is given.

To measure the detonation induction distance of these gas mixtures, a 6.4 meter long combustion tube has been used as a vessel in which the mixtures were ignited. Along the length of the tube, a series of thirteen holes and adapters serve as mounts for piezoelectric quartz pressure transducers. These Transducers are used to measure the pressure of combustion both during and after the formation of a detonation wave. The before and after measurements refer to the position in the tube at which they are taken. Figure 1 shows the combustion tube configuration.

The particular gas mixture under consideration is allowed to flow into the combustion tube through the ignitor which contains an orifice. The internal pressure within the tube is allowed to rise to the desired level of either one, one half or two atmospheres. When the desired pressure is reached, the flow of the mixture is shut off and the tube is sealed.

With all valves closed, the tube is at constant volume and the gas mixture is ignited from one end by passing a current through a piece of thin wire which is held in place on the ignitor and exposed to the gases. Ignition follows as a flame front rushes down the length of the tube and the process of the formation of a detonation wave occurs if the conditions are suitable (i.e. if the tube is long enough to allow transition from deflagration to detonation wave).

Following combustion, the tube is opened to the air via an exhaust line and the internal pressure is equalized with the ambient. A new ignitor is installed, and the tube is evacuated using a vacuum pump. The evacuation process removes water that has collected on the walls of the tube due to the combustion process. Following evacuation, the tube is filled once again and the experiment is repeated.

Two pressure transducers are used each run in conjunction with an oscilloscope. Data at one of the thirteen positions is taken per run even though two positions are used. For instance, transducers at stations one and two measure the wave pressure and velocity at station two. The probe at station one serves as a triggering device for the oscilloscope. By triggering two light beams to travel across the oscilloscope screen, a record of the passage of the detonation (or deflagration) wave is made and is recorded on a photograph.

The record takes the form of an abrupt jump in the lower beam which corresponds to a pressure input from the wave. The distance that the lower beam travels across the photograph corresponds to a velocity.

In particular, the height of the jump in the lower trace is directly measured from the photograph. The height is translated into a voltage output which in turn is translated into a pressure input. In a similar manner, the distance travelled by the lower beam before the jump corresponds to a time interval for the wave between transducers. This time is divided into the distance between the transducers and a velocity measurement is obtained.

Measurements at the rest of the transducer positions provides both a pressure and velocity profile throughout the combustion tube from which the detonation induction distance can be determined. The detonation induction distance is the distance from the ignitor to the point where the deflagration wave transitions into a detonation wave and is characterized by the high overshoot in both the velocity and the pressure profiles.

Using the experimental apparatus and procedure outlined above, the following four combustible gas mixtures were investigated:

1. $\frac{1}{2}O_2 + H_2 + \frac{1}{2}CO_2$

2. $\frac{1}{2}O_2 + H_2 + N_2$

3. $\frac{1}{2}O_2 + H_2 + He$

4. $\frac{1}{2}O_2 + H_2 + Ar$

Tables 1 through 12 hold data for the velocities (w_1) and the pressures (p_3) obtained as functions of the distance from the ignitor. Figures 4 through 27 contain plots of these data from which the characteristic peaks in pressure and velocity can be seen. The detonation induction distances obtained from these plots are found in Table 34. Furthermore, Figures 2 and 3 contain sample photographs obtained from the oscilloscope during four different runs of the combustion tube for several different gas mixtures.

B. continued

2. Theoretical Analysis

Although at this time there is no expression which permits the calculation of detonation induction distances of combustible gas mixtures, it is expected that our experimental determinations of induction distances together with theoretical calculations of various detonation parameters of selected systems will provide sufficient information to develop an empirical relationship for this important parameter. Since it appears that a high initial density of the unburned gas shortens the induction distance significantly, the induction distances of various H_2 + 1/2 O_2 + third gas mixtures have been measured at various initial conditions and the detonation parameters of these mixtures have been calculated for the so-called Chapman-Jouguet detonation ($w_3 = w_{a,3}$ or $M_{w_3} = 1$) in order to find out whether there is a relationship between any of these parameters and the detonation induction distance.

Iterations have been used to make these calculations which are started with estimates of the temperature, T_3, and pressure, p_3, of the combustion gas at the tail of the detonation wave. Subscript 1 denotes initial conditions and subscript 2 refers to the normal conditions before chemical changes have taken place.

Fairly reasonable estimates of p_3 and T_3 can be obtained from a consideration of heat addition to the

B. continued

2. continued

supersonic flow of a calorically perfect gas. When q Joules of heat are added to one kilogram of a moving gas, the pressure ratio across the resulting thermal wave is,

$$\left(\frac{p_3}{p_1}\right)^{M_{w_3}=1} = 1+\gamma\frac{q}{c_pT_1}\left[1+\sqrt{1+\frac{2/(\gamma+1)}{q/c_pT_1}}\,\right]$$

The dimensionless heat release factor, q/c_pT_1, can be expressed in terms of the combustion enthalpy of the fuel and the dimensionless specific heat of the combustion gas as follows,

$$\frac{q}{c_pT_1} = \delta\frac{\frac{|\Delta H^{T_1}_{comb,f}|}{\mathcal{R}T_1}}{\sum_i \nu_{i,o}\left(\frac{C_p}{\mathcal{R}}\right)_i^{T_{av}}}$$

where $|\Delta H_{comb,f}|$ is the absolute value of the combustion enthalpy of one mole of fuel at T_1, the $\nu_{i,o}$ are the mole numbers of the constituents of the undissociated combustion gas, and $\left(\frac{C_p}{\mathcal{R}}\right)_i^{T_{av}}$ is the average value of the dimensionless specific heat of the species i between T_1 and T_3. The correction factor δ ($\delta \leq 1$) is used to take dissociation into consideration. A suitable value for γ is of the order of 1.3 or slightly less.

An estimate of the temperature is obtained from the equation,

$$\left(\frac{T_3}{T_1}\right)^{M_{w_3}=1} = \left(\frac{p_3}{p_1}\right)^{M_{w_3}=1}\cdot\left(\frac{v_3}{v_1}\right)^{M_{w_3}=1}$$

B. continued

2. continued

where:

$$\left(\frac{v_3}{v_1}\right)^{M_{w_3}=1} = 1 + \frac{q}{c_p T_1}\left[1 - \sqrt{1 + \frac{2/(\gamma+1)}{q/c_p T_1}}\right]$$

With these estimates, the composition (mole fractions γ_i) of the combustion gas is calculated by an iterative procedure (inner loop). Since the estimated pressure most likely is not compatible with the estimated temperature, the correct pressure for the temperature is calculated next, also by an iterative procedure (middle loop). Finally, the correct temperature is calculated also by an iterative procedure from the conditions that $w_3 = w_{a,3}$ (outer loop). For each new pressure, there is a new composition and for each new temperature both pressure and composition have to be re-calculated. The following set of equations gives a complete survey of this procedure for a $H_2 + 1/2\ O_2 + \nu_{CO_2}\ CO_2$ gas mixture.

0: Enter .1 into the memory register for γ_{O_2} and the value of $f_{O_2} = \nu^g_{O_2}/\nu^g_{H_2}$ into both memory registers for f_{O_2} and $f^{calc}_{O_2}$.

Starting with $T_3^{est(o)}$ and $p_3^{est(o)}$ we have,

1: $T_3^{EST(n+1)} = T_3^{EST(n)} + x_{T_3}(W_3 - W_{a,3})$

where $x_{T_3} \sim 0.2$

B. continued

2. continued

2: $(T_3^{EST} - T_L)/100 = m$

3: $T_L = 100 \cdot (\text{INTEGER PART OF } (T_3^{EST}/100))$

4: $$p_3^{EST(n+1)} = p_3^{EST(n)} + x_p \cdot \left(p_3^{calc(n)} - p_3^{EST(n)} \right)$$

where $x_p \sim 0.5$

5: $$\left(a_{CO_2}^{T_L} + \Delta a_{CO_2}^{T_L} \cdot m\right) \cdot T_3^{.125} \cdot EXP\left\{\left[\left(\frac{H_f^\circ}{R}\right)_{CO} - \left(\frac{H_f^\circ}{R}\right)_{CO_2}\right] / T_3\right\} \sqrt{p_3} = K^{CO_2}$$

6: $$\left(a_{H_2O}^{T_L} + \Delta a_{H_2O}^{T_L} \cdot m\right) \sqrt{p_3} \cdot EXP\left[-\left(\frac{H_f^\circ}{R}\right)_{H_2O} / T_3\right] / \sqrt{T_3} = K^{H_2O}$$

7: $$\left(a_{OH}^{T_L} + \Delta a_{OH}^{T_L} \cdot m\right) / EXP\left[\left(\frac{H_f^\circ}{R}\right)_{OH} / T_3\right] = K^{OH}$$

8: $$\left(a_O^{T_L} + \Delta a_O^{T_L} \cdot m\right) \cdot \sqrt{T_3} / \left(\sqrt{p_3}\, EXP\left[\left(\frac{H_f^\circ}{R}\right)_O / T_3\right]\right) = K^O$$

B. continued

2. continued

9: $$\left(a_H^{T_L} + \Delta a_H^{T_L}\cdot m\right)\cdot\sqrt{T_3} \Big/ \left(\sqrt{p_3}\, EXP\left[\left(\frac{H_f^\circ}{R}\right)_H \Big/ T_3\right]\right) = K^H$$

10 $$\gamma_{O_2}^{EST(n+1)} = \gamma_{O_2}^{EST(n)} \cdot \left(f_{O_2} / f_{O_2}^{calc} \right)^{x_\gamma} \qquad x_\gamma \approx 3$$

11: $$\gamma_O = K^O \cdot \sqrt{\gamma_{O_2}^{EST}}$$

12: $$A = \left(K^{OH}\cdot\sqrt{\gamma_{O_2}^{EST}} + K^H\right)\cdot\left(1 + f_c/2\right)$$

where $f_C = \nu_C^g / \nu_{H_2}^g$

13: $$B = \left(K^{H_2O}\cdot\sqrt{\gamma_{O_2}^{EST}} + 1\right)\cdot\left(1 + f_c\right)$$

14: $$\gamma_{H_2} = \left\{\sqrt{\left(\frac{A}{2B}\right)^2 + \left(1 - \gamma_{O_2}^{EST} - \gamma_O\right)/B} - \frac{A}{2B}\right\}^2$$

15: $$\gamma_{H_2O} = K^{H_2O}\cdot\gamma_{H_2}\cdot\sqrt{\gamma_{O_2}^{EST}}$$

16: $$\gamma_{OH} = K^{OH}\cdot\sqrt{\gamma_{H_2}}\cdot\sqrt{\gamma_{O_2}^{EST}}$$

B. continued

2. continued

17: $\gamma_H = K^H \cdot \sqrt{\gamma_{H_2}}$

18: $\gamma_{H_2}^g = \gamma_{H_2O} + \gamma_{H_2} + (\gamma_{OH} + \gamma_H)/2$

19: $\gamma_C^g = f_c \cdot \gamma_{H_2}^g$

20: $\gamma_{CO} = \gamma_C^g / (1 + K^{CO_2} \cdot \sqrt{\gamma_{O_2}^{EST}})$

21: $\gamma_{CO_2} = \gamma_C^g - \gamma_{CO}$

22: $\gamma_{O_2}^g = \gamma_{CO_2} + \gamma_{O_2}^{EST} + (\gamma_{CO} + \gamma_{H_2O} + \gamma_{OH} + \gamma_O)/2$

23: $f_{O_2}^{calc} = \gamma_{O_2}^g / \gamma_{H_2}^g$

24: IF $ABS(f_{O_2}^{calc} - f_{O_2}) > 10^{-8}$; GTO LINE 10

B. continued

2. continued

25: $$\mathcal{M}_3 = \gamma_{O_2}^{g} \cdot \mathcal{M}_{O_2} + \gamma_C^{g} \cdot \mathcal{M}_C + \gamma_{H_2}^{g} \cdot \mathcal{M}_{H_2}$$

26: $$\gamma_{CO_2} \cdot \left[\left(\frac{H-E_0}{RT}\right)_{CO_2}^{T_L} + \Delta\left(\frac{H-E_0}{RT}\right)_{CO_2}^{T_L} \cdot m\right] + \gamma_{CO} \cdot \left[\left(\frac{H-E_0}{RT}\right)_{CO}^{T_L} + \Delta\left(\frac{H-E_0}{RT}\right)_{CO}^{T_L} \cdot m\right] +$$
$$\gamma_{H_2O} \cdot \left[\left(\frac{H-E_0}{RT}\right)_{H_2O}^{T_L} + \Delta\left(\frac{H-E_0}{RT}\right)_{H_2O}^{T_L} \cdot m\right] + \gamma_{OH} \left[\left(\frac{H-E_0}{RT}\right)_{OH}^{T_L} + \Delta\left(\frac{H-E_0}{RT}\right)_{OH}^{T_L} \cdot m\right] +$$
$$\gamma_{H_2} \cdot \left[\left(\frac{H-E_0}{RT}\right)_{H_2}^{T_L} + \Delta\left(\frac{H-E_0}{RT}\right)_{H_2}^{T_L} \cdot m\right] + \gamma_{O_2} \cdot \left[\left(\frac{H-E_0}{RT}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{RT}\right)_{O_2}^{T_L} \cdot m\right] +$$
$$\gamma_O \cdot \left[\left(\frac{H-E_0}{RT}\right)_{O}^{T_L} + \Delta\left(\frac{H-E_0}{RT}\right)_{O}^{T_L} \cdot m\right] + \gamma_H \cdot 2.5 = \left(\frac{h-e_0}{RT}\right)_{CG}^{T_3}$$

27: $$\left[T_3 \cdot \left(\frac{h-e_0}{RT}\right)_{CG}^{T_3} - \gamma_{CO_2} \cdot 47286 - \gamma_{CO} \cdot 33598 -\right.$$
$$\gamma_{H_2O} \cdot 28736 + \gamma_{OH} \cdot 4675 + \gamma_O \cdot 29685 +$$
$$\left.\gamma_H \cdot 25982\right] \Big/ \mathcal{M}_{CG}^{T_3} = \left(\frac{h_f}{R}\right)_{CG}^{T_3}$$

B. continued

2. continued

28: $$\frac{v_3}{v_1} = (T_3 \cdot p_1 \cdot \mathfrak{M}_1)/(T_1 \cdot p_3 \cdot \mathfrak{M}_3)$$

29: $$p_3^{calc} = p_1\left[1 + 2 \cdot \frac{\mathfrak{M}_1}{T_1} \cdot \left\{\left(\frac{h_f}{R}\right)_{CG}^{T_3} - \left(\frac{h_f}{R}\right)_{MIX}^{T_1}\right\} \Big/ \left(1 + \frac{v_3}{v_1}\right)\right]$$

30: IF ABS$(p_3^{calc} - p_3^{EST}) > 10^{-8}$; GTO LINE 4

31: $$\gamma_{CO_2} \cdot \left[\left(\frac{C_p}{R}\right)_{CO_2}^{T_L} + \Delta\left(\frac{C_p}{R}\right)_{CO_2}^{T_L} \cdot m\right] + \gamma_{CO} \cdot \left[\left(\frac{C_p}{R}\right)_{CO}^{T_L} + \Delta\left(\frac{C_p}{R}\right)_{CO}^{T_L} \cdot m\right] +$$
$$\gamma_{H_2O} \cdot \left[\left(\frac{C_p}{R}\right)_{H_2O}^{T_L} + \Delta\left(\frac{C_p}{R}\right)_{H_2O}^{T_L} \cdot m\right] + \gamma_{OH} \cdot \left[\left(\frac{C_p}{R}\right)_{OH}^{T_L} + \Delta\left(\frac{C_p}{R}\right)_{OH}^{T_L} \cdot m\right] +$$
$$\gamma_{H_2} \cdot \left[\left(\frac{C_p}{R}\right)_{H_2}^{T_L} + \Delta\left(\frac{C_p}{R}\right)_{H_2}^{T_L} \cdot m\right] + \gamma_{O_2} \cdot \left[\left(\frac{C_p}{R}\right)_{O_2}^{T_L} + \Delta\left(\frac{C_p}{R}\right)_{O_2}^{T_L} \cdot m\right] +$$
$$\gamma_{O} \cdot \left[\left(\frac{C_p}{R}\right)_{O}^{T_L} + \Delta\left(\frac{C_p}{R}\right)_{O}^{T_L} \cdot m\right] + \gamma_{H} \cdot 2.5 = \left(\frac{C_p}{R}\right)_{CG}^{T_3}$$

32: $$\left(\frac{C_p}{R}\right)_{CG}^{T_3} \Big/ \left[\left(\frac{C_p}{R}\right)_{CG}^{T_3} - 1\right] = \gamma_{CG,FROZEN}^{T_3}$$

B. continued

2. continued

The condition for the stable detonation wave (Chapman-Jouguet) is $w_3 = w_{a,3}$ where $w_{a,3}$ is the equilibrium speed of sound which means that chemical changes occur in the equilibrium combustion gas as the sound wave traverses it. Therefore, the effective specific heat ratio, $\gamma^{T_3}_{CG,eff}$ has to be calculated:

$$\gamma^{T_3}_{CG,EFF} = \frac{\left(\frac{c_p}{R}\right)^{T_3}_{CG} + \left\lfloor \frac{\Delta H^{(\ell)}}{RT} \right\rfloor \cdot \left[a_{\ell j} \right]^{-1} \cdot \left\{ \frac{\Delta H^{(j)}}{RT} \right\}}{\left(\frac{c_p}{R}\right)^{T_3}_{CG} - 1 + \left\lfloor \frac{\Delta H^{(\ell)}}{RT} - \Delta\nu^{(\ell)} \right\rfloor \cdot \left[b_{\ell j} \right]^{-1} \cdot \left\{ \frac{\Delta H^{(j)}}{RT} - \Delta\nu^{(j)} \right\}} \cdot$$

$$\frac{1 + \left\lfloor \frac{\Delta H^{(\ell)}}{RT} - \Delta\nu^{(\ell)} \right\rfloor \cdot \left[b_{\ell j} \right]^{-1} \cdot \left\{ \Delta\nu^{(j)} \right\}}{1 + \left\lfloor \frac{\Delta H^{(\ell)}}{RT} \right\rfloor \cdot \left[a_{\ell j} \right]^{-1} \cdot \left\{ \Delta\nu^{(j)} \right\}}$$

The coefficients of the two square matrices in this expression are given by the following equations:

$$b_{\ell,j} = \sum_i \frac{\nu_i^{(\ell)} \cdot \nu_i^{(j)}}{\eta_i}$$

B. continued

2. continued

and:

$$a_{\ell j} = b_{\ell j} - \Delta\nu^{(\ell)} \cdot \Delta\nu^{(j)}$$

where ℓ and j refer to the chemical change and $\nu_i^{(\ell)}$ is the stoichiometric mole number of species i in chemical change ℓ. Also,

$$\Delta\nu^{(\ell)} \equiv \sum_i \nu_i^{(\ell)}$$

($\nu_i^{(\ell)}$ on the right hand side of the equation are counted positive and those on the left are negative) is the change of mole numbers of chemical change ℓ. With the following order of five chemical changes occurring in the combustion gas,

1. $1/2\ O_2 \rightleftharpoons O$ $\quad \Delta\nu^{(O)} = 1/2$ $\quad \ell = j = (O)$
2. $1/2\ H_2 \rightleftharpoons H$ $\quad \Delta\nu^{(H)} = 1/2$ $\quad \ell = j = (H)$
3. $1/2\ O_2 + 1/2\ H_2 \rightleftharpoons OH$ $\quad \Delta\nu^{(OH)} = 0$ $\quad \ell = j = (OH)$
4. $1/2\ O_2 + CO \rightleftharpoons CO_2$ $\quad \Delta\nu^{(CO_2)} = -1/2$ $\quad \ell = j = (CO_2)$
5. $1/2\ O_2 + H_2 \rightleftharpoons H_2O$ $\quad \Delta\nu^{(H_2O)} = -1/2$ $\quad \ell = j = (H_2O)$

we have:

33: $$b_{11} = \frac{(-\frac{1}{2}) \cdot (-\frac{1}{2})}{\gamma_{O_2}} + \frac{1 \cdot 1}{\gamma_O}$$

B. continued

2. continued

34: $$b_{12} = \frac{(-\frac{1}{2})\cdot 0}{\gamma_{O_2}} + \frac{1\cdot 0}{\gamma_O} + \frac{0\cdot(-\frac{1}{2})}{\gamma_{H_2}} + \frac{0\cdot 1}{\gamma_H} = 0 = b_{21}$$

35: $$b_{13} = \frac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\gamma_{O_2}} + \frac{1\cdot 0}{\gamma_O} + \frac{0\cdot(-\frac{1}{2})}{\gamma_{H_2}} + \frac{0\cdot 1}{\gamma_{OH}} = b_{31}$$

36: $$b_{14} = \frac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\gamma_{O_2}} + \frac{1\cdot 0}{\gamma_O} + \frac{0\cdot(-1)}{\gamma_{CO}} + \frac{0\cdot 1}{\gamma_{CO_2}} = b_{41}$$

37: $$b_{15} = \frac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\gamma_{O_2}} + \frac{1\cdot 0}{\gamma_O} + \frac{0\cdot(-1)}{\gamma_{H_2}} + \frac{0\cdot 1}{\gamma_{H_2O}} = b_{51}$$

38: $$b_{22} = \frac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\gamma_{H_2}} + \frac{1\cdot 1}{\gamma_H}$$

39: $$b_{23} = \frac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\gamma_{H_2}} + \frac{1\cdot 0}{\gamma_H} + \frac{0\cdot(-\frac{1}{2})}{\gamma_{O_2}} + \frac{0\cdot 1}{\gamma_{OH}} = b_{32}$$

40: $$b_{24} = 0 \qquad = b_{42}$$

B. continued

2. continued

41: $b_{25}= \dfrac{(-\frac{1}{2})\cdot(-1)}{\eta_{H_2}} + 0 + 0 + 0 \qquad = b_{52}$

42: $b_{33}= \dfrac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\eta_{O_2}} + \dfrac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\eta_{H_2}} + \dfrac{1\cdot 1}{\eta_{OH}}$

43: $b_{34}= \dfrac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\eta_{O_2}} + 0 + 0 + 0 + 0 \qquad = b_{43}$

44: $b_{35}= \dfrac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\eta_{O_2}} + \dfrac{(-\frac{1}{2})\cdot(-1)}{\eta_{H_2}} + 0 + 0 \qquad = b_{53}$

45: $b_{44}= \dfrac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\eta_{O_2}} + \dfrac{(-1)\cdot(-1)}{\eta_{CO}} + \dfrac{1\cdot 1}{\eta_{CO_2}}$

46: $b_{45}= \dfrac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\eta_{O_2}} + 0 + 0 + 0 + 0 \qquad = b_{54}$

47: $b_{55}= \dfrac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\eta_{O_2}} + \dfrac{(-\frac{1}{2})\cdot(-\frac{1}{2})}{\eta_{H_2}} + \dfrac{1\cdot 1}{\eta_{H_2O}}$

B. continued

2. continued

Now,

$$\left[a_{\ell j}\right] = \left[b_{\ell j}\right] - \begin{bmatrix} .25 & .25 & 0 & -.25 & -.25 \\ .25 & .25 & 0 & -.25 & -.25 \\ 0 & 0 & 0 & 0 & 0 \\ -.25 & -.25 & 0 & .25 & .25 \\ -.25 & -.25 & 0 & .25 & .25 \end{bmatrix}$$

The five elements of the row, $\left\lfloor \frac{\Delta H^{(\ell)}}{\mathcal{R}T} \right\rfloor$, and column $\left\{ \frac{\Delta H^{(j)}}{\mathcal{R}T} \right\}$, matrices are,

48: $$\frac{\Delta H^{(O)}}{\mathcal{R}T} = \left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L} \cdot m + \frac{29685}{T_3} - \frac{1}{2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} \cdot m\right]$$

49: $$\frac{\Delta H^{(H)}}{\mathcal{R}T} = 2.5 + \frac{25982}{T_3} - \frac{1}{2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} \cdot m\right]$$

50: $$\frac{\Delta H^{(OH)}}{\mathcal{R}T} = \left(\frac{H-E_0}{\mathcal{R}T}\right)_{OH}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{OH}^{T_L} \cdot m + \frac{4675}{T_3} - \frac{1}{2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} \cdot m + \left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} \cdot m\right]$$

51: $$\frac{\Delta H^{(CO_2)}}{\mathcal{R}T} = \left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO_2}^{T_L} \cdot m - \frac{47286}{T_3} - \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO}^{T_L} \cdot m + \frac{1}{2}\left\{\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} \cdot m\right\}\right]$$

52: $$\frac{\Delta H^{(H_2O)}}{\mathcal{R}T} = \left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2O}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2O}^{T_L} \cdot m - \frac{28736}{T_3} - \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} \cdot m + \frac{1}{2}\left\{\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} \cdot m\right\}\right]$$

B. continued

2. continued

with the notation $a^{-1}_{\ell j}$ for the elements of the inverse of the $[a_{\ell j}]$ matrix, the multiplication of the $\left[\frac{\Delta H^{(\ell)}}{\mathcal{R}T}\right]$ by $[a_{\ell j}]^{-1}$ matrix leads to the following five elements of the resulting row matrix,

53: $$A^{O} = \frac{\Delta H^{(O)}}{\mathcal{R}T}\cdot a^{-1}_{11} + \frac{\Delta H^{(H)}}{\mathcal{R}T}\cdot a^{-1}_{12} + \frac{\Delta H^{(OH)}}{\mathcal{R}T}\cdot a^{-1}_{13} + \frac{\Delta H^{(CO_2)}}{\mathcal{R}T}\cdot a^{-1}_{14} + \frac{\Delta H^{(H_2O)}}{\mathcal{R}T}\cdot a^{-1}_{15}$$

54: $$A^{H} = \frac{\Delta H^{(O)}}{\mathcal{R}T}\cdot a^{-1}_{12} + \frac{\Delta H^{(H)}}{\mathcal{R}T}\cdot a^{-1}_{22} + \frac{\Delta H^{(OH)}}{\mathcal{R}T}\cdot a^{-1}_{23} + \frac{\Delta H^{(CO_2)}}{\mathcal{R}T}\cdot a^{-1}_{24} + \frac{\Delta H^{(H_2O)}}{\mathcal{R}T}\cdot a^{-1}_{25}$$

55: $$A^{OH} = \frac{\Delta H^{(O)}}{\mathcal{R}T}\cdot a^{-1}_{13} + \frac{\Delta H^{(H)}}{\mathcal{R}T}\cdot a^{-1}_{23} + \frac{\Delta H^{(OH)}}{\mathcal{R}T}\cdot a^{-1}_{33} + \frac{\Delta H^{(CO_2)}}{\mathcal{R}T}\cdot a^{-1}_{34} + \frac{\Delta H^{(H_2O)}}{\mathcal{R}T}\cdot a^{-1}_{35}$$

56: $$A^{CO_2} = \frac{\Delta H^{(O)}}{\mathcal{R}T}\cdot a^{-1}_{14} + \frac{\Delta H^{(H)}}{\mathcal{R}T}\cdot a^{-1}_{24} + \frac{\Delta H^{(OH)}}{\mathcal{R}T}\cdot a^{-1}_{34} + \frac{\Delta H^{(CO_2)}}{\mathcal{R}T}\cdot a^{-1}_{44} + \frac{\Delta H^{(H_2O)}}{\mathcal{R}T}\cdot a^{-1}_{45}$$

57: $$A^{H_2O} = \frac{\Delta H^{(O)}}{\mathcal{R}T}\cdot a^{-1}_{15} + \frac{\Delta H^{(H)}}{\mathcal{R}T}\, a^{-1}_{25} + \frac{\Delta H^{(OH)}}{\mathcal{R}T}\cdot a^{-1}_{35} + \frac{\Delta H^{(CO_2)}}{\mathcal{R}T}\cdot a^{-1}_{45} + \frac{\Delta H^{(H_2O)}}{\mathcal{R}T}\cdot a^{-1}_{55}$$

B. continued

2. continued

Multiplication of this row matrix by the column matrix $\left\{\frac{\Delta H^{(j)}}{RT}\right\}$ leads to,

58: $$a = A^{O} \cdot \frac{\Delta H^{(O)}}{RT} + A^{H} \cdot \frac{\Delta H^{(H)}}{RT} + A^{OH} \cdot \frac{\Delta H^{(OH)}}{RT} + A^{CO_2} \cdot \frac{\Delta H^{(CO_2)}}{RT} + A^{H_2O} \cdot \frac{\Delta H^{(H_2O)}}{RT}$$

and multiplication by the column matrix $\left\{\Delta \nu^{(j)}\right\}$ leads to:

59: $$a' = A^{O} \cdot \Delta\nu^{(O)} + A^{H} \cdot \Delta\nu^{(H)} + A^{OH} \cdot \Delta\nu^{(OH)} + A^{CO_2} \cdot \Delta\nu^{(CO_2)} + A^{H_2O} \cdot \Delta\nu^{(H_2O)}$$

Proceeding in a similar manner to evaluate the products

$$\left\lfloor \frac{\Delta H^{(e)}}{RT} - \Delta\nu^{(e)} \right\rfloor \cdot \left[b_{e_j} \right]^{-1} \cdot \left\{ \frac{\Delta H^{(j)}}{RT} - \Delta\nu^{(j)} \right\}$$

and

$$\left\lfloor \frac{\Delta H^{(e)}}{RT} - \Delta\nu^{(e)} \right\rfloor \cdot \left[b_{e_j} \right]^{-1} \cdot \left\{ \Delta\nu^{(j)} \right\}$$

we obtain,

60: $$B^{O} = \left(\frac{\Delta H^{(O)}}{RT} - \Delta\nu^{(O)}\right) \cdot b_{11}^{-1} + \left(\frac{\Delta H^{(H)}}{RT} - \Delta\nu^{(H)}\right) \cdot b_{12}^{-1} + \left(\frac{\Delta H^{(OH)}}{RT} - \Delta\nu^{(OH)}\right) \cdot b_{13}^{-1}$$
$$+ \left(\frac{\Delta H^{(CO_2)}}{RT} - \Delta\nu^{(CO_2)}\right) \cdot b_{14}^{-1} + \left(\frac{\Delta H^{(H_2O)}}{RT} - \Delta\nu^{(H_2O)}\right) \cdot b_{15}^{-1}$$

$$61:\quad B^{(H)} = \left(\frac{\Delta H^{(O)}}{\Re T} - \Delta\nu^{(O)}\right)\cdot b_{12}^{-1} + \left(\frac{\Delta H^{(H)}}{\Re T} - \Delta\nu^{(H)}\right)\cdot b_{22}^{-1} + \left(\frac{\Delta H^{(OH)}}{\Re T} - \Delta\nu^{(OH)}\right)\cdot b_{23}^{-1} + \left(\frac{\Delta H^{(CO_2)}}{\Re T} - \Delta\nu^{(CO_2)}\right)\cdot b_{24}^{-1} + \left(\frac{\Delta H^{(H_2O)}}{\Re T} - \Delta\nu^{(H_2O)}\right)\cdot b_{25}^{-1}$$

$$62:\quad B^{(OH)} = \left(\frac{\Delta H^{(O)}}{\Re T} - \Delta\nu^{(O)}\right)\cdot b_{13}^{-1} + \left(\frac{\Delta H^{(H)}}{\Re T} - \Delta\nu^{(H)}\right)\cdot b_{23}^{-1} + \left(\frac{\Delta H^{(OH)}}{\Re T} - \Delta\nu^{(OH)}\right)\cdot b_{33}^{-1} + \left(\frac{\Delta H^{(CO_2)}}{\Re T} - \Delta\nu^{(CO_2)}\right)\cdot b_{34}^{-1} + \left(\frac{\Delta H^{(H_2O)}}{\Re T} - \Delta\nu^{(H_2O)}\right)\cdot b_{35}^{-1}$$

$$63:\quad B^{(CO_2)} = \left(\frac{\Delta H^{(O)}}{\Re T} - \Delta\nu^{(O)}\right)\cdot b_{14}^{-1} + \left(\frac{\Delta H^{(H)}}{\Re T} - \Delta\nu^{(H)}\right) b_{24}^{-1} + \left(\frac{\Delta H^{(OH)}}{\Re T} - \Delta\nu^{(OH)}\right)\cdot b_{34}^{-1} + \left(\frac{\Delta H^{(CO_2)}}{\Re T} - \Delta\nu^{(CO_2)}\right)\cdot b_{44}^{-1} + \left(\frac{\Delta H^{(H_2O)}}{\Re T} - \Delta\nu^{(H_2O)}\right)\cdot b_{45}^{-1}$$

$$64:\quad B^{(H_2O)} = \left(\frac{\Delta H^{(O)}}{\Re T} - \Delta\nu^{(O)}\right)\cdot b_{15}^{-1} + \left(\frac{\Delta H^{(H)}}{\Re T} - \Delta\nu^{(H)}\right)\cdot b_{25}^{-1} + \left(\frac{\Delta H^{(OH)}}{\Re T} - \Delta\nu^{(OH)}\right)\cdot b_{35}^{-1} + \left(\frac{\Delta H^{(CO_2)}}{\Re T} - \Delta\nu^{(CO_2)}\right)\cdot b_{45}^{-1} + \left(\frac{\Delta H^{(H_2O)}}{\Re T} - \Delta\nu^{(H_2O)}\right)\cdot b_{55}^{-1}$$

$$65:\quad b = B^{O}\cdot\left(\frac{\Delta H^{(O)}}{\Re T} - \Delta\nu^{(O)}\right) + B^{H}\cdot\left(\frac{\Delta H^{(H)}}{\Re T} - \Delta\nu^{(H)}\right) + B^{OH}\left(\frac{\Delta H^{(OH)}}{\Re T} - \Delta\nu^{(OH)}\right) + B^{CO_2}\cdot\left(\frac{\Delta H^{(CO_2)}}{\Re T} - \Delta\nu^{(CO_2)}\right) + B^{H_2O}\cdot\left(\frac{\Delta H^{(H_2O)}}{\Re T} - \Delta\nu^{(H_2O)}\right)$$

$$66:\quad b' = B^{O}\cdot\Delta\nu^{(O)} + B^{H}\cdot\Delta\nu^{(H)} + B^{OH}\cdot\Delta\nu^{(OH)} + B^{CO_2}\cdot\Delta\nu^{(CO_2)} + B^{H_2O}\cdot\Delta\nu^{(H_2O)}$$

67: $$\gamma^{T_3}_{CG\,EFF} = \left[\left(\frac{c_p}{R}\right)^{T_3}_{CG} + a\right]\cdot(1+b') \Big/ \left\{\left[\left(\frac{c_p}{R}\right)^{T_3}_{CG} - 1 + b\right]\cdot(1+a')\right\}$$

68: $$W_{a,3} = \sqrt{\gamma^{T_3}_{CG\,EFF}\cdot \mathcal{R}\cdot T_3^{EST} \Big/ \mathfrak{M}^{T_3}_{CG}}$$

69: $$W_1^{C.-J.} = \sqrt{\mathcal{R} T_1 \left(\frac{p_3}{p_1} - 1\right) \Big/ \left\{\mathfrak{m}_1\cdot\left(1 - \frac{v_3}{v_1}\right)\right\}}$$

70: $$W_3 = W_1^{C.-J.} \cdot \frac{v_3}{v_1}$$

71: IF ABS $(W_3 - W_{a,3}) > 10^{-7}$; GTO LINE 1

END

C. Measurements Of Flame Speeds Of H_2-O_2-Third Gas Mixtures At Low Initial Temperatures

For these experiments, a new nozzle type burner has been constructed and tested. With this burner very well defined flame cones can be obtained even at high Reynolds numbers. The rather wide burner tube has a length of slightly more than 150 cm. and can be cooled by liquid nitrogen or other cryogenic coolants. Photographs of some flames obtained in preliminary experiments are shown in Figure 28. Since the conical part of the burner was not cooled, ice was formed at the tip of the burner and caused considerable distortion of the flame.

To eliminate this difficulty a shield through which dry nitrogen is passed has been placed around the burner tip. One side of the four sided 20 inch high shield consists of plexiglass for observation and photographing the flame.

D. DETONATION RESULTS AND CONCLUSIONS

In previous experiments[1], it was observed that the detonation induction distance of hydrogen-oxygen-third gas mixtures decreased as initial temperature decreased. In the experiments presented here, the same trend but a much smaller effect was observed as the initial pressure of the gas mixtures was increased.

For the gas mixtures used in this experiment as well as several others that contained either greater or lesser amounts of the third gas constituent, detonation parameters were calculated for the stable Chapman-Jouguet detonation wave. The results of these calculations are shown in Tables 13 to 32. Plots of the ratio of p_3/p_1 as a function of the initial temperature, T_1, are shown in Figures 30a to 30d. These plots show that this ratio (which is directly proportional to the relative energy transfer from the downstream burned gases to the gases at the tail of the detonation wave) does not vary significantly with initial pressure but does change appreciably with initial temperature especially in the 100 ^{o}K range.

By observing the tabulated values of w_1 and u_3 it is clear that these parameters decrease in value as the initial temperature is increased and that this decrease consistently occurs for all of the gas mixtures considered. The burned gas temperature, T_3,

D. continued

shows the same trend for mixtures that do not contain nitrogen. However, in mixtures containing at least 30% nitrogen ($1/2\ O_2 + H_2 + 1.88\ N_2$) the temperature, T_3, first decreases and then increases as the initial temperature is increased.

Further experiments and analysis are required to determine the precise relationship between initial temperature and detonation induction distance. It appears from these experiments and calculations that the relationship between initial density and the induction distance is not a simple one.

II. EFFECT OF HEAT ADDITION ON THE PRESSURE PROFILE OF AN ESTABLISHED SUBSONIC FLOW OF AIR

An analysis was made to investigate the effect of heat addition without mass addition by using an electric arc heater which is available in our laboratory. However, it was found that even at very low mach numbers the heat generated by this arc heater is too small to produce noticeable pressure changes in the flow field. Therefore, a tube has been designed in which hydrogen can be burned in air. It is presently under construction. In the meantime, a theoretical analysis of these experiments has been started so that these data can be compared to those obtained from the experiment. A previous analysis does not include the effect of mass addition and chemical changes.

Section III.

Performance Of A Supersonic Ramjet At Flight Mach Numbers Ranging From 1 To 10

For ramjets flying at an altitude of 100000 feet (T_∞= 233.1 K and p_∞= .01068 Atm.) and fueled either with liquid propane ($C_3H_8 + 5\ O_2 + 18.8\ N_2$) or with liquid or gaseous hydrogen ($H_2 + .5\ O_2 + 1.88\ N_2$) the specific thrust, F_s, the thrust specific fuel consumption, F_{sfc}, the thermodynamic efficiency, η_{th}, the overall efficiency, η_o, the diffuser inlet and exit areas A_i and A_{DE} respectively and the nozzle exit area, A_e, were calculated for two different diffuser configurations (dS = 0 and normal shock wave at inlet) and the subsonic and supersonic combustion modes. The complete details of the procedures and calculations are given for the diffuser in part A, for the combustion chamber in part B, and for the nozzle exit in part C. The results are tabulated and graphed in part D along with a general discussion of the data.

A. The Diffuser

The calculation of the diffuser exit conditions (T^o_{DE}, p^o_{DE}, T_{DE}, p_{DE} and u_{DE}) are based on the following Conditions and Assumptions:

1) The deceleration of the air entering the diffuser is adiabatic.

2) Thermodynamic and Chemical equilibrium prevails everywhere in the diffuser at all times.

A. continued

3) The freestream conditions are known : T_∞, p_∞, u_∞

4) Air consists of one mole of oxygen ($\mathcal{M}_{O_2}$ = 31.9988 kg/kmol) and 3.76 moles of nitrogen ($\mathcal{M}_{N_2}$ = 28.0134 kg/kmol) such that $\mathcal{M}_{air}$ = 28.85067 kg/kmol.

5) The diffuser exit speed u_{DE} as well as the diffuser exit Mach number, M_{DE}, can be calculated only when the combustion chamber exit Mach number, M_c, is specified. However, the stagnation conditions at the diffuser exit can be calculated without the knowledge of M_c. This interdependence between u_{DE} and u_c exists only when it is assumed that the cross sectional area of the combustion chamber, A_c, is constant. Also, parallel fuel injection is assumed (i.e. $A_c = A_f + A_{DE}$). Thus, there are two different procedures for calculating the conditions at the exit of the combustion chamber; one when only the stagnation conditions at the diffuser exit ($u_{DE} = C$ and u_c or better yet M_c is specified) are calculated and the other when u_{DE} or M_{DE} is specified. When u_{DE} is specified, u_c must be calculated. When u_{DE} is specified, care must be taken such that values which lead to choking are not used. Since it is not possible to predict the exact range of these speeds it is advantageous to specify M_c. Although this procedure is very versatile because it permits the calculation of all subsonic and supersonic combustion modes, at high freestream speeds it may lead to impractical diffuser configurations (requiring airflow acceleration) when high subsonic values

A. continued

5) continued

of M_c are specified in conjunction with diffusers having normal shock waves at their inlets. All of these difficulties can be avoided easily by making calculations both for specified values of u_{DE} (or M_{DE}) where M_c is then calculated, and for specified values of M_c where u_{DE} must then be calculated.

6) Since the performance of a ramjet depends very much on the efficiency of diffusion, it is necessary to know the value of the diffuser efficiency. Although there are many expressions in use to determine the efficiency of a diffuser, all of them are a measure of the fact that the actual diffusion process is irreversible and therefore, causes an increase in the entropy of the air. Unfortunately, neither diffuser efficiencies nor the entropy increase occurring in a diffuser can be calculated from the gasdynamic equations. Diffuser efficiencies are thus determined from experiment. For a theoretical analysis of diffusers it is, therefore, necessary to specify either the increase in entropy which occurs as the airflow is decelerated or to give the diffuser efficiency which in this study will be written as,

$$\eta_D = \frac{p^o_{DE} - p_\infty}{p^o_\infty - p_\infty}$$

where p^o_{DE} is the actual stagnation pressure at the diffuser exit and p^o_∞ is the isentropic stagnation pressure associated with the

A. continued

6) continued

freestream.

To demonstrate the effect of $\mathcal{M}_D$ on the performance of a ramjet the calculations will be made for $p^o_{DE} = p^o_a$ ($\mathcal{M}_D = 1$ and $\frac{\Delta S}{\mathcal{R}} = 0$) and for $p^o_{DE} = p^o_i$ where p^o_i is the isentropic stagnation pressure behind the normal shock wave occurring at the diffuser inlet. The procedure for these calculations can be used without modifications to calculate the diffuser exit conditions for specified values of $\mathcal{M}_D$ or $\frac{\Delta S}{\mathcal{R}}$.

The equations relating the unknown temperatures and pressures at the diffuser exit to the specified initial conditions are : the continuity equation, the energy equation, the equation of state, the entropy equation and the equations for the chemical equilibrium constants.

The energy equation is written in the following form,

$$\left(\frac{h_f}{\mathcal{R}}\right)^{T_\infty}_{air} + \frac{u_\infty^2}{2\mathcal{R}} = \left(\frac{h_f}{\mathcal{R}}\right)^{T^o_\infty}_{eq.air} = \left(\frac{h_f}{\mathcal{R}}\right)^{T^o_{DE}}_{eq.air} = \left(\frac{h_f}{\mathcal{R}}\right)^{T_{DE}}_{eq.air} + \frac{u_{DE}^2}{2\mathcal{R}}$$

where $\left(\frac{h_f}{\mathcal{R}}\right)^T = \frac{T}{\mathfrak{M}}\left(\frac{h_f}{\mathcal{R}T}\right)^T$ and $\left(\frac{h_f}{\mathcal{R}T}\right)^T = \sum_i \gamma_i \left(\frac{H_f}{\mathcal{R}T}\right)^T_i$

with $\left(\frac{H_f}{\mathcal{R}T}\right)^T_i = \left(\frac{H-E_o}{\mathcal{R}T}\right)^T_i + \left(\frac{H^o_f}{\mathcal{R}}\right)_i \cdot \frac{1}{T}$

A. continued

The reduced sensible enthalpies, $\left(\frac{H-E_0}{\mathcal{R}T}\right)_i^T$, of the various species, i, can be found in tables (e.g. NBS, JANNAF, Wolfson and Dunn ARL 62-390 and AFOSR TR 3641, Nov. 1975) for temperatures ranging from 100 to 6000 K. The absolute formation enthalpies, $\left(\frac{H_f^\circ}{\mathcal{R}}\right)_i$, at T = 0 K are constants which are also listed in many thermodynamic tables.

The calculations of the diffuser exit conditions are started with a zero estimate of the temperature which is obtained from the energy equation written for a calorically perfect gas,

$$T_{DE}^{EST(0)} = T_\infty + \frac{u_\infty^2 - u_{DE}^2}{2\Gamma R_{air}}$$

where $\Gamma = 3.5$ when u_∞ is low and $\Gamma = 4.5$ when u_∞ is high ($M_\infty = 10$). When M_{DE} is specified, the speed u_{DE} is replaced by the product of the speed of sound at the diffuser exit and the M_{DE}:

$$u_{DE} = M_{DE}\sqrt{\gamma_{air}\mathcal{R}T_{DE}/\mathcal{M}_{air}}$$

Substitution leads to,

$$T_{DE}^{EST(0)} = \left(T_\infty + \frac{u_\infty^2}{2\Gamma R_{air}}\right) \Big/ \left(1 + \frac{\gamma - 1}{2} M_{DE}^2\right)$$

When high speed flows ($M_\infty > 6$) are decelerated to subsonic speeds, the high temperature of the decelerated air causes the nitrogen and oxygen molecules to dissociate into atoms and

A. continued

also to combine to form nitric oxide, NO. The composition of the dissociated air depends on temperature and pressure because these chemical changes are accompanied by a change in the total mole number of the gas mixture. Therefore, a zero order estimate of the pressure, p_{DE}, is also needed before the iterative calculations of the correct values can be started. Such an estimate is obtained from the polytropic relationship,

$$p_{DE}^{EST(0)} = p_\infty \cdot \left(T_{DE}^{EST(0)} / T_\infty \right)^{\kappa}$$

where κ may be slightly less than two for cases involving a normal shock at the diffuser inlet and slightly larger than four when high Mach numbers and isentropic diffusers are considered. For the given conditions and the stated assumptions very accurate values of T_{DE} and p_{DE} (or T^{o}_{DE} and p^{o}_{DE}) are obtained by iterative calculations in which improved estimates are established by means of the following empirical equation,

$$T_{DE}^{EST(n+1)} = T_{DE}^{EST(n)} + X_T \left[\left(\frac{h_s}{\mathcal{R}}\right)_{air}^{T_\infty} - \left(\frac{h_s}{\mathcal{R}}\right)_{eq.\,air}^{T_{DE}} + \frac{u_\infty^2 - u_{DE}^2}{2\mathcal{R}} \right]$$

The updating factor, X_T , is of the order of three. Improved estimates of the pressure are obtained by means of the entropy according to the following relationship,

A. continued

$$p_{DE}^{EST(n+1)} = p_{DE}^{EST(n)} \cdot \left[\left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_{DE}^{EST(n)}} \Big/ \left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_i} \right]^{X_p}$$

where X_p is approximately 25 and

$$\left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_i} = \left(\frac{S}{\mathcal{R}}\right)_{air}^{T_\infty}$$

when the diffusion process is assumed to be isentropic, and

$$\left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_i} > \left(\frac{S}{\mathcal{R}}\right)_{air}^{T_\infty}$$

when the deceleration is irreversible. The magnitude of the increase in entropy $\left(\frac{\Delta S}{\mathcal{R}} = \left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_{DE}} - \left(\frac{S}{\mathcal{R}}\right)_{air}^{T_\infty}\right)$ depends on the design of the diffuser. In general it is impossible to calculate an accurate value of $\frac{\Delta S}{\mathcal{R}}$. However, for supersonic flows the increase in entropy can be calculated readily when it is assumed that the increase is caused only by a normal shock wave at the diffuser inlet while any subsequent speed changes in the diffuser are reversible.

For the ambient conditions prevailing at an altitude of 100000 feet ($T_\infty = 233.1$ K and $p_\infty = .01068$ Atm.) the isentropic and normal shock stagnation temperatures and pressures, the entropy increases across the normal shock wave, and the corresponding diffuser efficiencies are tabulated in Table 33, for flight Mach numbers, M_∞, ranging from 1 to 10.

These calculations show that the efficiency of the diffuser with a normal shock wave at the inlet decreases very strong-

A. continued

ly with increasing flight Mach number, whereas the increase in entropy even at $M_\infty = 10$ is only 24.47%. The table also shows that chemical changes up to $M_\infty = 6$ are insignificant ($T^o_{DE} = T^o_\infty$). However, at higher flight Mach numbers T^o_{DE} becomes less than T^o_∞ and at $M_\infty = 10$ the difference between the two temperatures is no more than 400 K because of the endothermic chemical changes which occur more readily at the lower pressure resulting from the normal shock deceleration. Enthalpy-entropy diagrams are shown in figures 29 a and b for a diffuser with a shock-free inlet and for the case where there is a normal shock wave at the inlet. Whereas for subsonic flight speeds the calculation of the diffuser exit conditions are simple because in this temperature range air can be treated as a calorically perfect gas, for supersonic flight speeds the calculations of temperature, pressure, formation enthalpy and entropy becomes quite involved because in these temperature ranges the specific heats of the gas constituents are strongly dependent on temperature and chemical changes occur. Depending on the flight Mach number and the design of the diffuser the calculations of one, two or all three of the following processes may be needed for a complete analysis of the airflow.

1) Diffuser with normal shock wave at the inlet

This process requires the calculation of $T_i^{N.S.}$, $p_i^{N.S.}$ and $\left(\frac{s}{\mathcal{R}}\right)_{eq\ air}^{T_i^{N.S.}}$ which are the temperature, pressure and entropy behind the normal shock wave respectively. Even when a

A. continued

1) continued

supersonic diffuser is to be used so that no normal shock wave occurs at the inlet, the knowledge of the entropy increase $(\frac{S}{\mathcal{R}})^{T_i^{N.S.}}_{eq\ air} - (\frac{S}{\mathcal{R}})^{T_\infty}_{air}$ across the shock wave will be of value because it may serve as a guide for the design of efficient supersonic diffusers.

2) General deceleration of an airflow

This process requires the calculation of T^o_{DE} and p^o_{DE} (or T_{DE} and p_{DE}) for specified values of $(\frac{S}{\mathcal{R}})^{T_{DE}}_{eq\ air}$, and u_{DE} (or M_{DE}). For instance, the case of truly isentropic diffusion, $(\frac{S}{\mathcal{R}})^{T_{DE}}_{eq\ air} = (\frac{S}{\mathcal{R}})^{T_\infty}_{eq\ air}$, may be used as a reference value or a number of cases with very small increases in entropy, $(\frac{S}{\mathcal{R}})^{T_{DE}}_{eq\ air} \geq (\frac{S}{\mathcal{R}})^{T_\infty}_{eq\ air}$, may be analyzed to obtain a survey. The entropy increase across a normal shock wave, $(\frac{S}{\mathcal{R}})^{T_i^{N.S.}}_{eq\ air} - (\frac{S}{\mathcal{R}})^{T_\infty}_{eq\ air}$, can be used as a measure to specify the magnitude of the actual increase in entropy. When subsonic diffusers with a normal shock wave at the inlet are used, $(\frac{S}{\mathcal{R}})^{T_{DE}}_{eq\ air}$ may be greater than $(\frac{S}{\mathcal{R}})^{T_i^{N.S.}}_{eq\ air}$.

3) Deceleration of an airflow to a specified stagnation pressure, p^o_{DE}.

Reasonable values of p^o_{DE} can be established by using p^o_∞ and $p_i^{o\ N.S.}$, as a guide. The actual stagnation pressure may be expressed in terms of a desired diffuser efficiency,

A. continued

3) continued

$$p^{o}_{DE} = p_\infty + \eta_D \cdot \left(p^{o}_\infty - p_\infty\right)$$

As shown in Table 33 at Mach numbers below 6, $T^{o}_{DE} = T_i^{oN.S.} = T^{o}_\infty$ whereas at high Mach numbers $T_i^{o\,N.S.} < T^{o}_\infty$ and $T^{o}_{DE} \leq T^{o}_\infty$ where the equal sign applies only to truly isentropic diffusion processes.

<u>Equations for calculating $T_i^{N.S.}$, $p_i^{N.S.}$ and $u_i^{N.S.}$ behind a normal shock wave at M_∞.</u>

First, with $\gamma = 1.4$ when $M_\infty \leq 3$, and $\gamma < 1.4$ for $M_\infty > 3$, the zero order values of $T_i^{N.S.}$ and $p_i^{N.S.}$ are calculated,

0 : $$T_i^{N.S.\,EST(0)} = T_\infty \left(\frac{2}{\gamma+1} + \frac{\gamma-1}{\gamma+1} M_\infty^2\right) \cdot \left(\frac{2\gamma}{\gamma+1} - \frac{\gamma-1}{\gamma+1} \Big/ M_\infty^2\right)$$

1: $$p_i^{N.S.\,EST(0)} = p_\infty \cdot \left(\frac{2\gamma}{\gamma+1} M_\infty^2 - \frac{\gamma-1}{\gamma+1}\right) = p_i^{(M-C)} = p_i^{(ST-C)}$$

where p_i^{M-C} is an approximate value of $p_i^{N.S.}$ which will be obtained (see line 23) from a combination of the <u>m</u>omentum and <u>c</u>ontinuity equations and p_i^{St-C} is an approximate value of $p_i^{N.S.}$ which will be obtained from a combination of the equation of <u>st</u>ate and the <u>c</u>ontinuity equations (see line 24). Now enter a zero order approximation for the mole fraction of nitrogen, e.g. $\mathcal{M}_{N_2} = 0.7$ and set the first value of $f_{N_2}^{calc} = 3.76$.

A. continued

3) continued

The approximate values of $T_i^{N.S.}$ and $p_i^{N.S.}$ are then improved by means of the following empirical relation,

$$2: \quad T_i^{N.S.\ EST(N+1)} = T_i^{N.S.\ EST(N)} \left(p_i^{(M-C)\,EST(N)} \Big/ p_i^{(St-C)\,EST(N)} \right)^{x_T}$$

where x_T is approximately 0.2 and,

$$3: \quad p_i^{N.S.\ EST(N+1)} = p_i^{(M-C)\,EST(N)} + x_p \left(p_i^{(M-C)\,EST(N)} - p_i^{(St-C)\,EST(N)} \right)$$

where x_p is approximately 0.1 .

By repeating the iterative calculations which consist of an inner loop (to iterate for the airflow composition) and an outer loop (to iterate for the true value of $T_i^{N.S.}$) until the difference between $p_i^{(M-C)}$ and $p_i^{(St-C)}$ is as small as desired (e.g. until $\left| p_i^{(M-C)} - p_i^{(St-C)} \right|$ is less than 10^{-8}), very accurate values will be obtained. The values of the thermodynamic functions at any temperature are obtained by linear interpolation in the appropriate 100 degree temperature interval. Defining the variable m,

$$4: \quad m = \left(T_i^{N.S.\ EST} - T_L \right) / 100$$

where $T_L = (100 \cdot (\text{integer part of } (T_i^{N.S.}/100)))$ we obtain

A. continued

3) continued

$$5:\ \left(a_{NO}^{T_L}+\Delta a_{NO}^{T_L}\cdot m\right)\Big/EXP\left(10799/T_i^{N.S.EST}\right) = K^{NO}$$

where $a_{NO}^{T_L}$ is the coefficient (at T_L) of the equilibrium constant for the equilibrium $\frac{1}{2}N_2 + \frac{1}{2}O_2 \rightleftharpoons NO$ and $\Delta a_{NO}^{T_L} = a_{NO}^{(T_L+100)} - a_{NO}^{T_L}$ (see AFOSR RPT 3641, Nov.1975).

Similarly,

$$6:\ \left(a_O^{T_L}+\Delta a_O^{T_L}\cdot m\right)\sqrt{T_i^{N.S.EST}}\Big/\sqrt{p_i^{N.S.EST}}\ EXP\left(29685/T_i^{N.S.EST}\right) = K^{O}$$

$$7:\ \left(a_N^{T_L}+\Delta a_N^{T_L}\cdot m\right)\sqrt{T_i^{N.S.EST}}\Big/\sqrt{p_i^{N.S.EST}}\ EXP\left(56613/T_i^{N.S.EST}\right) = K^{N}$$

$$8:\ u_\infty = M_\infty\cdot\sqrt{\gamma_{air}^{T_\infty}\,\mathcal{R}\,T_\infty\Big/M_{air}}$$

The approximate value of the nitrogen mole fraction, γ_{N_2}, is improved by an empirical equation which uses the specified f_{N_2} (3.76) and the calculated value $f_{N_2}^{calc}$ as follows,

$$9:\ \gamma_{N_2}^{EST(n+1)} = \gamma_{N_2}^{EST(n)}\left(3.76/f_{N_2}^{calc}\right)^{x_\gamma}$$

where x_γ is approximately .3. The calculation of the mole fractions proceeds in the following manner,

$$10:\ \left(K^{NO}\sqrt{\gamma_{N_2}^{EST}} + K^{O}\right)/2 = A$$

A. Continued

3) continued

11: $K^{N} \cdot \sqrt{\gamma_{N_2}^{EST}} = \gamma_N$

12: $\left\{ \sqrt{A^2 + 1 - \gamma_{N_2} - \gamma_N} - A \right\}^2 = \gamma_{O_2}$

13: $K^{O} \cdot \sqrt{\gamma_{O_2}} = \gamma_O$

14: $K^{NO} \cdot \sqrt{\gamma_{O_2}} \cdot \sqrt{\gamma_{N_2}} = \gamma_{NO}$

15: $\gamma_{O_2} + (\gamma_{NO} + \gamma_O)/2 = \gamma_{O_2}^{g}$

16: $\gamma_{N_2} + (\gamma_{NO} + \gamma_N)/2 = \gamma_{N_2}^{g}$

17: $\gamma_{N_2}^{g} / \gamma_{O_2}^{g} = f_{N_2}^{calc}$

18: If $\left| f_{N_2}^{calc} - f_{N_2} \right| > 10^{-8}$ go back to line 9

19: $\gamma_{N_2}^{g} \cdot \mathfrak{M}_{N_2} + \gamma_{O_2}^{g} \cdot \mathfrak{M}_{O_2} = \mathfrak{M}_{eq.\,air}^{T_i}$

20: $$\gamma_{N_2}\left[\left(\frac{H-E_0}{\Re T}\right)_{N_2}^{T_L} + \Delta\left(\frac{H-E_0}{\Re T}\right)_{N_2}^{T_L} \cdot m\right] + \gamma_{O_2}\left[\left(\frac{H-E_0}{\Re T}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{\Re T}\right)_{O_2}^{T_L} \cdot m\right] +$$

$$\gamma_{NO}\left[\left(\frac{H-E_0}{\Re T}\right)_{NO}^{T_L} + \Delta\left(\frac{H-E_0}{\Re T}\right)_{NO}^{T_L} \cdot m\right] + \gamma_{O}\left[\left(\frac{H-E_0}{\Re T}\right)_{O}^{T_L} + \Delta\left(\frac{H-E_0}{\Re T}\right)_{O}^{T_L} \cdot m\right] +$$

$$\gamma_{N}\left[\left(\frac{H-E_0}{\Re T}\right)_{N}^{T_L} + \Delta\left(\frac{H-E_0}{\Re T}\right)_{N}^{T_L} \cdot m\right] = \left(\frac{h-e_0}{RT}\right)_{eq.\,air}^{T_i}$$

A. continued

3) continued

21: $$\left(T_i^{N.S.}\left(\frac{h-e_0}{RT}\right)_{eq.air}^{T_i^{N.S.}} + \gamma_{NO}\cdot 10799 + \gamma_{O}\cdot 29685 + \gamma_{N}\cdot 56613\right)\Big/ \mathcal{M}_{eq.air}^{T_i^{N.S.}} = \left(\frac{h_S}{\mathcal{R}}\right)_{eq.air}^{T_i^{N.S.}}$$

22: $$u_i = \sqrt{u_\infty^2 + 2\mathcal{R}\left[\left(\frac{h_S}{\mathcal{R}}\right)_{air}^{T_\infty} - \left(\frac{h_S}{\mathcal{R}}\right)_{eq.air}^{T_i^{N.S.}}\right]}$$

23: $$p_i^{M-C} = p_\infty\cdot\left(1 + \frac{u_\infty}{R_{air}T_\infty}\cdot\left(1 - \frac{u_i}{u_\infty}\right)\right)$$

24: $$p_i^{ST-C} = p_\infty\cdot T_i^{N.S.}\mathcal{M}_{air}u_\infty \Big/ T_\infty \mathcal{M}_{eq.air}^{T_i^{N.S.}} u_i$$

25: If $\left|p_i^{M-C} - p_i^{St-C}\right| > 10^{-8}$ Go To Line 2

26: $$\gamma_{N_2}\left[(c_s)_{N_2}^{T_L} + \Delta(c_s)_{N_2}^{T_L}\cdot m\right] + \gamma_{O_2}\cdot\left[(c_s)_{O_2}^{T_L} + \Delta(c_s)_{O_2}^{T_L}\cdot m\right] + \gamma_{NO}\cdot\left[(c_s)_{NO}^{T_L} + \Delta(c_s)_{NO}^{T_L}\cdot m\right] +$$
$$\gamma_{O}\left[(c_s)_{O}^{T_L} + \Delta(c_s)_{O}^{T_L}\cdot m\right] + \gamma_{N}\left[(c_s)_{N}^{T_L} + \Delta(c_s)_{N}^{T_L}\cdot m\right] = (c_s)_{eq.air}^{T_i^{N.S.}}$$

27: $$\gamma_{N_2}\ln\gamma_{N_2} + \gamma_{O_2}\ln\gamma_{O_2} + \gamma_{NO}\ln\gamma_{NO} + \gamma_{O}\ln\gamma_{O} + \gamma_{N}\ln\gamma_{N} = \left(\sum_i \gamma_i \ln\gamma_i\right)_{eq.air}^{T_i^{N.S.}}$$

28: $$\left[(c_s)_{eq.air}^{T_i^{N.S.}}\cdot\ln T_i - \left(\sum_i \gamma_i\cdot\ln\gamma_i\right)_{eq.air}^{T_i^{N.S.}} - \ln p_i^{ST}\right]\Big/ \mathcal{M}_{eq.air}^{T_i^{N.S.}} = \left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_i^{N.S.}}$$ END

A. continued

Equations for calculating conditions Of Temperature, Pressure and Flowspeed At Diffuser exit produced by reversible and irreversible decelerations

For these calculations the area ratio A_{DE}/A_i and the entropy increase ($\Delta s \geq 0$) must be known. However, it is rather impractical to specify reasonable values of the area ratio. Therefore, instead of this ratio the flow speed, u_{DE}, (or the corresponding diffuser exit Mach number M_{DE}) will be specified where $u_{DE} = 0$ ($M_{DE} = 0$) is included and used to calculate the stagnation conditions (T^o_{DE} and p^o_{DE}) at the diffuser exit.

First the stagnation enthalpy of the airflow is calculated, (equation 0 is good for T_∞ between 100 and 400 K)

$$0: \left(\frac{h_s}{\mathcal{R}}\right)_{air}^{T_\infty} = \Big\{3.5\,T_\infty + \big[2238.9/(EXP(2238.9/T_\infty)-1) + 3.76\cdot 3351.6/(EXP(3351.6/T_\infty)-1)\big]/4.76 - 0.333(2.07905 + 3.76\cdot 2.862)/4.76\Big\}/\mathcal{M}_{air}$$

$$1: \left(\frac{h_s}{\mathcal{R}}\right)_{eq.air}^{T^o_\infty} = \left(\frac{h_s}{\mathcal{R}}\right)_{air}^{T_\infty} + \frac{u_\infty^2}{2\mathcal{R}} = \left(\frac{h_s}{\mathcal{R}}\right)_{eq.air}^{T_{DE}} + \frac{u_{DE}^2}{2\mathcal{R}} = \left(\frac{h_s}{\mathcal{R}}\right)_{eq.air}^{T^o_{DE}}$$

Then the entropy of the freestream air is calculated according to the following equation:

$$2: \left(\frac{s}{\mathcal{R}}\right)_{air}^{T_\infty} = \left(C_{s,air}^{T_\infty}\cdot \ln T_\infty - \left(\sum_i \gamma_i \ln \gamma_i\right)_{air} - \ln p_\infty\right)/\mathcal{M}_{air}$$

where $C_{s,air}^{T_\infty}$ is the entropy coefficient of air obtained from Figure 30. $(\sum \gamma_i \ln \gamma_i)_{air}$ = -.51407

A. continued

Zero order estimates of temperature and pressure are obtained from the following equations after either $^{s}u_{DE}$ or $^{s}M_{DE}$ has been specified; (the superscripts denotes that these values are specified)

If M_{DE} is specified ($^{s}M_{DE} > 0$) GTO line 4, otherwise,

$$3: \quad T_{DE}^{EST(0)} = T_{\infty} + \frac{u_{\infty}^{2} - u_{DE}^{2}}{2\Gamma R_{air}} \qquad \text{Go To Line 5}$$

where Γ is approximately 3.5 when u_{∞} is low and Γ is approximately 4.5 when u_{∞} is high ($M_{\infty} \sim 10$).

$$4: \quad T_{DE}^{EST(0)} = \left(T_{\infty} + \frac{u_{\infty}^{2}}{2\Gamma R_{air}}\right) \Big/ \left(1 + \frac{\gamma - 1}{2} M_{DE}^{2}\right)$$

$$5: \quad p_{DE}^{EST(0)} = \left(T_{DE}^{EST(0)} \big/ T_{\infty}\right)^{\Gamma} \cdot p_{\infty}$$

The approximate values of T_{DE} and p_{DE} are then improved by executing the following iterative calculations,

$$6: \quad T_{DE}^{EST(m+1)} = T_{DE}^{EST(m)} + X_{T}\left[\left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_{\infty}^{o}} - \left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_{DE}^{o}(calc.)}\right]$$

where X_T is approximately 3 and $\left(\frac{h_f}{\mathcal{R}}\right)_{eq\ air}^{T_{DE}^{o\ calc}} = \left(\frac{h_f}{\mathcal{R}}\right)_{eq\ air}^{T_{\infty}^{o}}$ when this loop is started.

$$7: \quad m = \left(T_{DE}^{EST} - T_{L}\right) \big/ 100$$

where now $T_L = 100 \cdot \left(\text{INTEGER PART OF } \left(T_{DE}^{EST} / 100\right)\right)$

A. continued

$$8:\ \left(a_{NO}^{T_L}+\Delta a_{NO}^{T_L}\cdot m\right)\Big/ EXP\left(10799/T_{DE}^{EST}\right) = K^{NO}$$

$$9:\ p_{DE}^{EST(n+1)} = p_{DE}^{EST(n)}\cdot\left[\left(\frac{S}{R}\right)_{eq.air}^{T_{DE}^{EST}}\Big/\left\{\left(\frac{S}{R}\right)_{air}^{T_\infty}+\Delta\left(\frac{S}{R}\right)\right\}\right]^{X_p}$$

where X_p ia approximately 25.

$\frac{\Delta S}{R}$ is equal to zero for isentropic decelerations. When a normal shock wave is present at the diffuser inlet but the resulting subsonic flow in the diffuser can be considered to be isentropic, the entropy increase (through the shock) is, $\left(\frac{\Delta S}{R}\right)_{N.S.} = \left(\frac{S}{R}\right)_{eq\ air}^{T_i^{N.S.}} - \left(\frac{S}{R}\right)_{air}^{T_\infty}$.

Values of $\left(\frac{\Delta S}{R}\right)$ less than $\left(\frac{\Delta S}{R}\right)_{N.S.}$ represent diffusers with oblique shocks. For a diffuser employing a normal shock wave at the inlet, $\left(\frac{\Delta S}{R}\right)$ is actually slightly larger than $\left(\frac{\Delta S}{R}\right)_{N.S.}$ because the flow through the diffuser is not reversible.

$$10:\ \left(a_{O}^{T_L}+\Delta a_{O}^{T_L}\cdot m\right)\Big/\left(\sqrt{p_{DE}^{EST}}\ EXP\left(29685/T_{DE}^{EST}\right)\right) = K^{O}$$

$$11:\ \left(a_{N}^{T_L}+\Delta a_{N}^{T_L}\cdot m\right)\Big/\left(\sqrt{p_{DE}^{EST}}\ EXP\left(56613/T_{DE}^{EST}\right)\right) = K^{N}$$

ENTER $\gamma_{N_2}^{EST(0)} = 0.7$ and $\xi_{N_2}^{calc} = 3.76$

$$12:\ \gamma_{N_2}^{EST(n+1)} = \gamma_{N_2}^{EST(n)}\cdot\left(3.76/\xi_{N_2}^{calc}\right)^{X_\gamma}$$ where $x_\gamma \sim 0.2$

$$13:\ \left(K^{NO}\cdot\sqrt{\gamma_{N_2}^{EST}}+K^{O}\right)/2 = A$$

A. continued

14: $K^{N} \cdot \sqrt{\gamma_{N_2}^{EST}} = \gamma_N$

15: $\left\{ \sqrt{A^2 + 1 - \gamma_{N_2}^{EST} - \gamma_N} - A \right\}^2 = \gamma_{O_2}$

16: $K^{O} \cdot \sqrt{\gamma_{O_2}} = \gamma_O$

17: $K^{NO} \cdot \sqrt{\gamma_{O_2}} \cdot \sqrt{\gamma_{N_2}^{EST}} = \gamma_{NO}$

18: $\gamma_{O_2} + (\gamma_{NO} + \gamma_O)/2 = \gamma_{O_2}^{g}$

19: $\gamma_{N_2} + (\gamma_{NO} + \gamma_N)/2 = \gamma_{N_2}^{g}$

20: $\gamma_{N_2}^{g} / \gamma_{O_2}^{g} = \xi_{N_2}^{calc}$

21: IF ABS$(\xi_{N_2}^{calc} - 3.76) > 10^{-8}$; GTO LINE 12

22: $\gamma_{N_2}^{g} \cdot \mathcal{M}_{N_2} + \gamma_{O_2}^{g} \cdot \mathcal{M}_{O_2} = \mathcal{M}_{eq.\,air}^{TDE}$

A. continued

23: $$\gamma_{N_2}\cdot\left(c_{s,N_2}^{T_L}+\Delta c_{s,N_2}^{T_L}\cdot m\right)+\gamma_{O_2}\cdot\left(c_{s,O_2}^{T_L}+\Delta c_{s,O_2}^{T_L}\cdot m\right)+\gamma_{NO}\cdot\left(c_{s,NO}^{T_L}+\Delta c_{s,NO}^{T_L}\cdot m\right)+$$
$$\gamma_{O}\cdot\left(c_{s,O}^{T_L}+\Delta c_{s,O}^{T_L}\cdot m\right)+\gamma_{N}\cdot\left(c_{s,N}^{T_L}+\Delta c_{s,N}^{T_L}\cdot m\right)=c_{s,\,eq.air}^{T_{DE}}$$

24: $$\gamma_{N_2}\cdot\ln\gamma_{N_2}+\gamma_{O_2}\cdot\ln\gamma_{O_2}+\gamma_{NO}\cdot\ln\gamma_{NO}+\gamma_{O}\cdot\ln\gamma_{O}+\gamma_{N}\cdot\ln\gamma_{N}=\left(\sum_i\gamma_i\cdot\ln\gamma_i\right)_{eq.air}^{T_{DE}}$$

25: $$\left(c_{s,eq\,air}^{T_{DE}}\cdot\ln T_{DE}-\left(\sum_i\gamma_i\ln\gamma_i\right)_{eq.air}^{T_{DE}}-\ln p_{DE}\right)\Big/\mathcal{M}_{eq.air}^{T_{DE}}=\left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_{DE}}$$

26: If $\left|\left(\frac{S}{\mathcal{R}}\right)_{eq\ air}^{T_{DE}}-\left(\frac{S}{\mathcal{R}}\right)_{eq\ air}^{T_\infty}-\left(\frac{\Delta S}{\mathcal{R}}\right)\right|>10^{-8}$ Go To 9

27: $$\gamma_{N_2}\cdot\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L}+\Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L}\cdot m\right]+\gamma_{O_2}\cdot\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L}+\Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L}\cdot m\right]+$$
$$\gamma_{NO}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L}+\Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L}\cdot m\right]+\gamma_{O}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L}+\Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L}\cdot m\right]+$$
$$\gamma_{N}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L}+\Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L}\cdot m\right]=\left(\frac{h-e_0}{RT}\right)_{eq.air}^{T_{DE}}$$

A. continued

28: $\left(\left(\frac{h-e_0}{RT}\right)_{eq.air}^{T_{DE}} \cdot T_{DE} + \gamma_{NO} \cdot 10799 + \gamma_{O} \cdot 29685 + \gamma_{N} \cdot 56613 \right) \Big/ \mathcal{M}_{eq.air}^{T_{DE}} = \left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_{DE}(calc)} ;$

if ${}^{S}u_{DE} > 0$; GTO 32

29: $\gamma_{N_2} \left[\left(\frac{C_p}{\mathcal{R}}\right)_{N_2}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{N_2}^{T_L} \cdot m \right] + \gamma_{O_2} \left[\left(\frac{C_p}{\mathcal{R}}\right)_{O_2}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{O_2}^{T_L} \cdot m \right] +$

$\gamma_{NO} \left[\left(\frac{C_p}{\mathcal{R}}\right)_{NO}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{NO}^{T_L} \cdot m \right] + \gamma_{O} \left[\left(\frac{C_p}{\mathcal{R}}\right)_{O}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{O}^{T_L} \cdot m \right] +$

$\gamma_{N} \left[\left(\frac{C_p}{\mathcal{R}}\right)_{N}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{N}^{T_L} \cdot m \right] = \left(\frac{C_p}{R}\right)_{eq.air}^{T_{DE}}$

30: $\left(\frac{C_p}{R}\right)_{eq.air}^{T_{DE}} \Big/ \left[\left(\frac{C_p}{R}\right)_{eq.air}^{T_{DE}} - 1 \right] = \gamma_{eq.air}^{T_{DE}}$

31: $u_{DE} = {}^{S}M_{DE} \sqrt{\gamma_{eq.air}^{T_{DE}} \cdot \mathcal{R} \cdot T_{DE} \Big/ \mathcal{M}_{eq.air}^{T_{DE}}}$

32: $\left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_{DE}^{o}} = \left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_{DE}} + \frac{u_{DE}^2}{2\mathcal{R}}$

33: if $\left| \left(\frac{h_f}{\mathcal{R}}\right)_{eq\ air}^{T_{\infty}^{o}} - \left(\frac{h_f}{\mathcal{R}}\right)_{eq\ air}^{T_{DE}^{o}\ calc} \right| > 10^{-8}$ Go To 6

34: $A_i / \dot{m}_{air} = \mathcal{R} T_i \big/ (p_i \mathcal{M}_i u_i)$; END

A. Continued

Calculation of Diffuser Exit Conditions For a Specified Diffuser Efficiency

Whereas the preceding section provides the analysis of the performance of a diffuser for specified entropies, in practice it is usually more practical to specify the diffuser efficiency in terms of the stagnation pressure recovery,

$$\eta_D = \left(p^o_{DE} - p_\infty\right) / \left(p^o_\infty - p_\infty\right)$$

For a specified value of η_D (based on design and flow Mach number, M_∞) the stagnation pressure at the diffuser exit can be calculated as

$$p^o_{DE} = p_\infty + \eta_D \left(p^o_\infty - p_\infty\right)$$

after p^o_∞ for $\left(\frac{s}{\mathcal{R}}\right)^{T^o_\infty}_{eq.air} = \left(\frac{s}{\mathcal{R}}\right)^{T_\infty}_{air}$ has been calculated.

When p^o_{DE} is known and $u_{DE} = 0$ the calculation of T^o_{DE} is greatly simplified. The procedure consists of the following steps,

0: $$T^{o\,EST(0)}_{DE} = T_\infty + \frac{u^2_\infty}{2\Gamma\, R_{air}}$$

1: $$T^{o\,EST(n+1)}_{DE} = T^{o\,EST(n)}_{DE} + X_T\left[\left(\frac{h_f}{\mathcal{R}}\right)^{T^o_\infty}_{eq.air} - \left(\frac{h_f}{\mathcal{R}}\right)^{T^o_{DE}(calc)}_{eq.air}\right]$$

When starting the calculations, enter the value of $\left(\frac{h_f}{\mathcal{R}}\right)^{T^o_\infty}_{eq.air}$ also into the computer's memory register assigned to $\left(\frac{h_f}{\mathcal{R}}\right)^{T^o_{DE}(calc)}_{eq.air}$ and use $\eta^{EST(0)}_{N_2} = 0.7$, and enter 3.76 into the memory register for $\xi^{calc}_{N_2}$

A. Continued

2: $\left(T_{DE}^{\circ EST} - T_L\right) / 100 = m$

where as above $T_L = 100 \cdot$ (integar value of $\left(T_{DE}^{\circ EG} / 100\right.$))

3: $K^{NO} = \left(a_{NO}^{T_L} + \Delta a_{NO}^{T_L} \cdot m\right) / EXP\left(10799 / T_{DE}^{\circ EST}\right)$

4: $K^{O} = \left(a_O^{T_L} + \Delta a_O^{T_L} \cdot m\right) \cdot \sqrt{T_{DE}^{\circ EST}} \Big/ \left(\sqrt{\rho_{DE}^{\circ}}\ EXP\left(29685 / T_{DE}^{\circ EST}\right)\right)$

5: $K^{N} = \left(a_N^{T_L} + \Delta a_N^{T_L} \cdot m\right) \cdot \sqrt{T_{DE}^{\circ EST}} \Big/ \left(\sqrt{\rho_{DE}^{\circ}}\ EXP\left(56613 / T_{DE}^{\circ EST}\right)\right)$

6: $\gamma_{N_2}^{EST(n+1)} = \gamma_{N_2}^{EST(n)} \cdot \left(3.76 / \xi_{N_2}^{calc}\right)^{x_\gamma}$

where $x_\gamma \sim 0.3$

7: $\left(K^{NO} \sqrt{\gamma_{N_2}^{EST}} + K^{O}\right) / 2 = A$

8: $K^{N} \cdot \sqrt{\gamma_{N_2}^{EST}} = \gamma_N$

9: $\left\{\sqrt{A^2 + 1 - \gamma_{N_2} - \gamma_N} - A\right\}^2 = \gamma_{O_2}$

10: $K^{O} \cdot \sqrt{\gamma_{O_2}} = \gamma_O$

11: $K^{NO} \cdot \sqrt{\eta_{O_2}} \cdot \sqrt{\eta_{N_2}} = \eta_{NO}$

12: $\eta_{O_2} + (\eta_{NO} + \eta_O)/2 = \eta_{O_2}^{g}$

13: $\eta_{N_2} + (\eta_{NO} + \eta_N)/2 = \eta_{N_2}^{g}$

14: $\eta_{N_2}^{g} / \eta_{O_2}^{g} = f_{N_2}^{calc}$

15: IF ABS($f_{N_2}^{calc} - 3.76) > 10^{-8}$; GTO LINE 6

16: $\eta_{N_2}^{g} \cdot \mathfrak{M}_{N_2} + \eta_{O_2}^{g} \cdot \mathfrak{M}_{O_2} = \mathfrak{M}_{eq.\,air}^{T_{DE}^{o}}$

17: $$\eta_{N_2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L} \cdot m\right] + \eta_{O_2} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} \cdot m\right] +$$

$$\eta_{NO} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L} \cdot m\right] + \eta_O \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L} \cdot m\right] +$$

$$\eta_N \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L} \cdot m\right] = \left(\frac{h-e_0}{RT}\right)_{eq.\,air}^{T_{DE}^{o}}$$

18: $$\left(T_{DE}^{o}\left(\frac{h-e_0}{\mathcal{R}T}\right)_{eq.\,air}^{T_{DE}^{o}} + \eta_{NO} \cdot 10799 + \eta_O \cdot 29685 + \eta_N \cdot 56613\right) \Big/ \mathfrak{M}_{eq.\,air}^{T_{DE}^{o}} = \left(\frac{h_E}{\mathcal{R}}\right)_{eq.\,air}^{T_{DE}^{o}(calc)}$$

19: IF $ABS\left[\left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_{DE}^{o}(calc)} - \left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_\infty^o}\right] > 10^{-6}$; GTO LINE 1

To calculate the static temperature and pressure the entropy is needed. We obtain

$$20:\quad \eta_{N_2}\cdot\left(c_{s,N_2}^{T_L} + \Delta c_{s,N_2}^{T_L}\cdot m\right) + \eta_{O_2}\cdot\left(c_{s,O_2}^{T_L} + \Delta c_{s,O_2}^{T_L}\cdot m\right) +$$

$$\eta_{NO}\cdot\left(c_{s,NO}^{T_L} + \Delta c_{s,NO}^{T_L}\cdot m\right) + \eta_{O}\cdot\left(c_{s,O}^{T_L} + \Delta c_{s,O}^{T_L}\cdot m\right) +$$

$$\eta_{N}\cdot\left(c_{s,N}^{T_L} + \Delta c_{s,N}^{T_L}\cdot m\right) = c_{s,eq.air}^{T_{DE}^{o}}$$

With a specified value for u_{DE} (or M_{DE}) we have:

21: IF ${}^{s}M_{DE} > 0$; GTO LINE 23

$$22:\quad T_{DE}^{EST(0)} = T_{DE}^{o} - \frac{{}^{s}u_{DE}^{2}}{2\Gamma R_{air}}$$

$$23:\quad T_{DE}^{EST(0)} = T_{DE}^{o} \Big/ \left(1 + \frac{\gamma-1}{2}\,{}^{s}M_{DE}^{2}\right)$$

$$24:\quad P_{DE}^{EST(0)} = p_{DE}^{o}\cdot\left(T_{DE}^{EST(0)} \big/ T_{DE}^{o}\right)^{\Gamma}$$

$$25:\quad T_{DE}^{EST(n+1)} = T_{DE}^{EST(n)} + X_T\left[\left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_\infty^o} - \left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_{DE}^{o}(calc)}\right]$$

$$m = (T_{DE} - T_L)/100$$

where $T_L = 100 \cdot (\text{INTEGER PART OF}(T_{DE}/100))$

26: $K^{NO} = \left(a_{NO}^{T_L} + \Delta a_{NO}^{T_L} \cdot m\right) \Big/ EXP\left(10799/T_{DE}^{EST}\right)$

27: $p_{DE}^{EST(n+1)} = \left[\left(\frac{S}{R}\right)_{eq.air}^{T_{DE}^{EST(n)}} \Big/ \left(\frac{S}{R}\right)_{eq.air}^{T_{DE}^{o}}\right]^{x_p} \cdot p_{DE}^{EST(n)}$

where

28: $\left(\frac{S}{R}\right)_{eq.air}^{T_{DE}^{o}} = \left(c_{s,air}^{T_{DE}^{o}} \cdot \ln T_{DE}^{o} - \left(\sum_i \gamma_i \ln \gamma_i\right)_{eq.air}^{T_{DE}^{o}} - \ln p_{DE}^{o}\right) \Big/ \mathcal{M}_{eq.air}^{T_{DE}^{o}}$

29: $\left(a_O^{T_L} + \Delta a_O^{T_L} \cdot m\right) \sqrt{T_{DE}^{EST}} \Big/ \left(\sqrt{p_{DE}^{EST}}\; EXP\left(29685/T_{DE}^{EST}\right)\right) = K^O$

30: $\left(a_N^{T_L} + \Delta a_N^{T_L} \cdot m\right) \sqrt{T_{DE}^{EST}} \Big/ \left(\sqrt{p_{DE}^{EST}}\; EXP\left(56613/T_{DE}^{EST}\right)\right) = K^N$

Use $\gamma_{N_2}^{EST(0)} = 0.7$ and enter 3.76 into memory register for $f_{N_2}^{calc}$

31: $\gamma_{N_2}^{EST(n+1)} = \gamma_{N_2}^{EST(n)} \cdot \left(3.76/f_{N_2}^{calc}\right)^{x_\gamma}$

where $x_\gamma \sim 0.3$

32: $\left(K^{NO} \cdot \sqrt{\gamma_{N_2}^{EST}} + K^O\right)/2 = A$

33: $K^N \cdot \sqrt{\gamma_{N_2}^{EST}} = \gamma_N$

34: $\left\{\sqrt{A^2+1-\gamma_{N_2}-\gamma_N} - A\right\}^2 = \gamma_{O_2}$

35: $K^O \cdot \sqrt{\gamma_{O_2}} = \gamma_O$

36: $K^{NO} \cdot \sqrt{\gamma_{O_2}} \cdot \sqrt{\gamma_{N_2}} = \gamma_{NO}$

37: $\gamma_{O_2} + (\gamma_{NO} + \gamma_O)/2 = \gamma^g_{O_2}$

38: $\gamma_{N_2} + (\gamma_{NO} + \gamma_N)/2 = \gamma^g_{N_2}$

39: $\gamma^g_{N_2} / \gamma^g_{O_2} = \xi^{calc}_{N_2}$

40: IF ABS$(\xi^{calc}_{N_2} - 3.76) > 10^{-8}$; GOTO LINE 31

41: $\gamma^g_{N_2} \cdot \mathcal{M}_{N_2} + \gamma^g_{O_2} \cdot \mathcal{M}_{O_2} = \mathcal{M}^{T_{DE}}_{eq.\,air}$

42: $\gamma_{N_2} \cdot \left[c^{T_L}_{s,N_2} + \Delta c^{T_L}_{s,N_2} \cdot m\right] + \gamma_{O_2} \cdot \left[c^{T_L}_{s,O_2} + \Delta c^{T_L}_{s,O_2} \cdot m\right] + \gamma_{NO} \cdot \left[c^{T_L}_{s,NO} + \Delta c^{T_L}_{s,NO} \cdot m\right] +$

$\gamma_O \cdot \left[c^{T_L}_{s,O} + \Delta c^{T_L}_{s,O} \cdot m\right] + \gamma_N \cdot \left[c^{T_L}_{s,N} + \Delta c^{T_L}_{s,N} \cdot m\right] = c^{T_{DE}}_{s,eq.\,air}$

43: $\gamma_{N_2} \ln \gamma_{N_2} + \gamma_{O_2} \ln \gamma_{O_2} + \gamma_{NO} \ln \gamma_{NO} + \gamma_O \ln \gamma_O + \gamma_N \ln \gamma_N = \left(\sum_i \gamma_i \ln \gamma_i\right)^{T_{DE}}_{eq.\,air}$

44: $\left(c^{T_{DE}}_{s,eq.\,air} \cdot \ln T_{DE} - \left(\sum_i \gamma_i \ln \gamma_i\right)^{T_{DE}}_{eq.\,air} - \ln p_{DE}\right) / \mathcal{M}^{T_{DE}}_{eq.\,air} = \left(\frac{S}{\mathcal{R}}\right)^{T_{DE}}_{eq.\,air}$

45: $$\text{IF ABS}\left[\left(\frac{S}{R}\right)^{T_{DE}}_{eq.air} - \left(\frac{S}{R}\right)^{T^{\circ}_{DE}}_{eq.air}\right] > 10^{-8}\text{; GOTO LINE 27}$$

46: $$\gamma_{N_2}\cdot\left[\left(\frac{H-E_0}{RT}\right)^{T_L}_{N_2} + \Delta\left(\frac{H-E_0}{RT}\right)^{T_L}_{N_2}\cdot m\right] + \gamma_{O_2}\cdot\left[\left(\frac{H-E_0}{RT}\right)^{T_L}_{O_2} + \Delta\left(\frac{H-E_0}{RT}\right)^{T_L}_{O_2}\cdot m\right] +$$

$$\gamma_{NO}\cdot\left[\left(\frac{H-E_0}{RT}\right)^{T_L}_{NO} + \Delta\left(\frac{H-E_0}{RT}\right)^{T_L}_{NO}\cdot m\right] + \gamma_{O}\cdot\left[\left(\frac{H-E_0}{RT}\right)^{T_L}_{O} + \Delta\left(\frac{H-E_0}{RT}\right)^{T}_{O}\cdot m\right] +$$

$$\gamma_{N}\cdot\left[\left(\frac{H-E_0}{RT}\right)^{T_L}_{N} + \Delta\left(\frac{H-E_0}{RT}\right)^{T_L}_{N}\cdot m\right] = \left(\frac{h-e_0}{RT}\right)^{T_{DE}}_{eq.air}$$

47: $$\left(T_{DE}\cdot\left(\frac{h-e_0}{RT}\right)^{T_{DE}}_{eq.air} + \gamma_N\cdot 10799 + \gamma_O\, 29685 + \gamma_N\cdot 56613\right)\Big/ M^{T_{DE}}_{eq.air} = \left(\frac{h_e}{R}\right)^{T_{DE}(calc)}_{eq.air}$$

48: $$\text{IF } {}^{s}u_{DE} > 0\text{; GOTO LINE 52}$$

49: $$\gamma_{N_2}\cdot\left[\left(\frac{C_p}{R}\right)^{T_L}_{N_2} + \Delta\left(\frac{C_p}{R}\right)^{T_L}_{N_2}\cdot m\right] + \gamma_{O_2}\cdot\left[\left(\frac{C_p}{R}\right)^{T_L}_{O_2} + \Delta\left(\frac{C_p}{R}\right)^{T_L}_{O_2}\cdot m\right] +$$

$$\gamma_{NO}\cdot\left[\left(\frac{C_p}{R}\right)^{T_L}_{NO} + \Delta\left(\frac{C_p}{R}\right)^{T_L}_{NO}\cdot m\right] + \gamma_{O}\cdot\left[\left(\frac{C_p}{R}\right)^{T_L}_{O} + \Delta\left(\frac{C_p}{R}\right)^{T_L}_{O}\right] +$$

$$\gamma_{N}\cdot\left[\left(\frac{C_p}{R}\right)^{T_L}_{N} + \Delta\left(\frac{C_p}{R}\right)^{T_L}_{N}\right] = \left(\frac{C_p}{R}\right)^{T_{DE}}_{eq.air}$$

50: $$\left(\frac{C_p}{R}\right)^{T_{DE}}_{eq.air}\Big/\left(\left(\frac{C_p}{R}\right)^{T_{DE}}_{eq.air} - 1\right) = \gamma^{T}_{eq.air}$$

51: $u_{DE} = {}^{s}M_{DE}\sqrt{\gamma_{eq.air}^{T_{DE}} \cdot \mathcal{R}T_{DE} / \mathcal{M}_{eq.air}^{T_{DE}}}$

52: $\left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T^{\circ}_{DE}(calc)} = \left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_{DE}} + \frac{u_{DE}^2}{2\mathcal{R}}$

53: IF ABS $\left[\left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T^{\circ}_{\infty}} - \left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T^{\circ}_{DE}(calc)}\right] > 10^{-6}$; GTO LINE 25

54: $A_{DE}/\dot{m}_{air} = \mathcal{R}^{*}T_{DE}/(p_{DE}\,\mathcal{M}_{eq.air}^{T_{DE}}\,u_{DE})$; END

Since at flight Mach numbers less than six the temperature of the stagnated airflow practically does not depend on the diffuser exit pressure the calculations for a specified η_D are only needed when M_∞ is greater than six.

B. The Combustion Chamber

As pointed out above, the procedure for the calculation of the conditions at the exit of the combustion chamber depends on three parameters: 1) the area variation of the combustion chamber ($dA = 0$ or $dA > 0$); 2) the magnitude of u_{DE} or M_{DE}; and 3) the magnitude of u_c or M_c.

Only constant area duct combustion chambers will be discussed here. In this case u_{DE} (or M_{DE}) and u_c (or M_c) cannot be specified independently. When u_{DE} (or M_{DE}) is specified, u_c (or M_c) has a certain value which must be calculated and vice versa. When u_c (or M_c) is specified u_{DE} (or M_{DE}) must be calculated.

In practice it is advantageous to specify M_c instead of u_{DE} (or M_{DE}) because this procedure avoids the difficulties which arise when the selected value of M_{DE} (or u_{DE}) leads to choking. Therefore, this procedure will be discussed first. The analysis makes use of the energy equation, entropy equation, and the momentum equation. In the first part of these calculations T_c and u_c are calculated. Since the composition of the combustion gas depends on temperature and pressure, the iterative calculations must be started with both a $T_c^{est(o)}$ and a $p_c^{est(o)}$. The estimate of the temperature is somewhat difficult because at high flight Mach numbers the high temperature of the decelerated air entering the combustion chamber from the diffuser has a strong effect on the temperature of the combustion gas. Furthermore, the appreciable

B. continued

speed changes which occur under certain conditions make a comparison with the so-called adiabatic flame temperature impossible. Because of these facts the following relationship produces only a very rough estimate of T_c ,

$$T_c^{EST(0)} \sim T_\infty^{o} + f \cdot \left| \Delta h_{comb,fuel}^{T_\infty} \right| \sqrt{T_\infty / T_\infty^{o}} \Big/ (4.8\, R_{air})$$

An estimate of the combustion chamber pressure, p_c, can be obtained from the momentum equation for a calorically perfect gas according to which we can write,

$$p_c^{EST(0)} = p_{DE}^{o} \cdot \left(1+\gamma M_{DE}^2\right) \Big/ \left[\left(1+\gamma M_c^2\right)\left(1+\frac{\gamma-1}{2} M_{DE}^2\right)\right]$$

Since neither γ nor M_{DE} are known, they must be guessed. Estimates obtained from the above relation may differ significantly from the true value of p_c. In general it can be stated that $p_c < p_{DE}$ for subsonic combustion ($M_{DE} < 1$) whereas $p_c > p_{DE}$ for supersonic combustion ($M_{DE} > 1$). However, in all cases $p_c < p_c^o < p_{DE}^o$. Therefore, the following simple equation may be useful for obtaining a zero order estimate of the combustion chamber pressure,

$$p_c^{EST(0)} = p_{DE}^{o} \cdot x$$

where $0.6 \lesssim x \lesssim 0.9$. Whereas the correct values of T_c and u_c can be calculated easily from the energy equation, the correct value of p_c which is obtained from the condition that

B. continued

$A_c = A_{DE} + A_f$

$$p_c^{calc} = (1+f)\frac{\mathcal{R}T_c}{\mathcal{M}_{CG}^{T_c} u_c} \Big/ \left[\frac{\mathcal{R}T_{DE}}{\mathcal{M}_{eq\,air}^{T_{DE}} u_{DE} \cdot p_{DE}} + f\frac{101325}{u_f \cdot \rho_f}\right]$$

Obviously, can be calculated only after T_c, u_c, T_{DE}, u_{DE} and p_{DE} have been calculated. T_c and u_c are obtained by calculating

$$\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^o(calc)} = \left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c} + \frac{u_c^2}{2\mathcal{R}}$$

where

$$\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c} = \left[T_c\left(\frac{h-e_o}{RT}\right)_{CG}^{T_c} + \sum_i \gamma_i\left(\frac{H_f^o}{\mathcal{R}}\right)_i\right] \Big/ \mathcal{M}_{CG}^{T_c}$$

and $\left(\frac{h - e_o}{RT}\right)_{CG}^{T_c} = \sum_i \mathcal{M}_i \left(\frac{H - E_o}{\mathcal{R}T}\right)_i^{T_c}$

and comparing this calculated value of $\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^o}$ with the given value which is according to the energy equation,

$$\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^o} = \left[\left(\frac{h_f}{\mathcal{R}}\right)_{air}^{T_\infty} + \frac{u_\infty^2}{2\mathcal{R}} + f\left\{\left(\frac{h_f}{\mathcal{R}}\right)_{FUEL}^{T_f} + \frac{u_f^2}{2\mathcal{R}}\right\}\right] \Big/ (1+f)$$

The procedure of these calculations consists of the following sequence of equations and involves 6 loops for the iterative calculation of 1) the composition of the combustion gas, 2) the combustion chamber T_c and u_c, 3) the composition of the equilibrium air at the diffuser exit, 4) the pressure at the diffuser exit, p_{DE}, 5) the temperature at the diffuser exit, T_{DE}, and 6) the pressure in the combustion chamber p_c. A schematic of the looping procedure is shown in Figure 31.

B. continued

Begin the iteration:

0: $$\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^0} = \left[\left(\frac{h_f}{\mathcal{R}}\right)_{eq.air}^{T_\infty^0} + f \cdot \left\{\left(\frac{h_f}{\mathcal{R}}\right)_f^{T_f} + \frac{u_f^2}{2\mathcal{R}}\right\}\right] / (1+f)$$

1: $$p_c^{EST(0)} = p_{DE}^{0} \cdot x$$

where $0.6 \leq x \leq 0.9$ (0.6 for large values of M_{DE} and 0.9 for small values of M_{DE}).

2: $$T_c^{EST(0)} = T_\infty^0 + f \cdot \left|\Delta h_{comb,fuel}^{T_f}\right| \cdot \sqrt{T_\infty / T_\infty^0} \Big/ (4.8 R_{air})$$

3: $$\gamma_{N_2}^{EST(0)} = 6.75 \cdot f_{O_2} \big/ (1 + 9.52 \cdot f_{O_2}) \; ; \; \gamma_{O_2}^{EST(0)} = 0.01$$

where $f_{O_2} = \nu_{O_2}^g / \nu_{H_2}^g$ is the ratio of the global oxygen to global hydrogen in the fuel-air mixture.

4: $$p_c^{EST(n+1)} = p_c^{EST(n)} + x_p \left(p_c^{calc(n)} - p_c^{EST(n)}\right)$$

where x_p is approximately .95 since the calculated value of p_c is much closer to the correct value than the estimate. Before the calculations are started the value of $p_c^{est(o)}$ must also be entered into the memory register for p_c^{calc}.

B. continued

$$5: T_c^{EST(n+1)} = T_c^{EST(n)} + X_T\left[\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^o} - \left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^o(calc)}\right]$$

where X_T is approximately 3. Again, before the calculations are started the value of $(\frac{h_f}{\mathcal{R}})_{CG}^{T_c^o}$ must also be entered in the memory register for the value of $(\frac{h_f}{\mathcal{R}})_{CG}^{T_c^o\ calc}$. In addition the ratio of the global mole number of oxygen to the global mole number of the hydrogen in the ~~fuel~~ air mixture $f_{O_2} = \nu_{O_2}^g / \nu_{H_2}^g$ must be entered also into the register for the value of $f_{O_2}^{calc}$ and 3.76 into that of f_{N_2/O_2}^{calc}

$$6: (T_c - T_{L,c}) / 100 = m_c$$

where $T_{L,c}$ = 100· (integer part of $(T_c/100)$)

$$7: (a_{CO_2}^{T_L} + \Delta a_{CO_2}^{T_L} \cdot m_c) \cdot T_c^{.125} EXP\left\{\left[\left(\frac{H_f^o}{\mathcal{R}}\right)_{CO} - \left(\frac{H_f^o}{\mathcal{R}}\right)_{CO_2}\right] / T_c\right\} \sqrt{p_c} = K^{CO_2}$$

$$8: (a_{H_2O}^{T_L} + \Delta a_{H_2O}^{T_L} \cdot m_c) \cdot \sqrt{p_c}\, EXP[-(H_f^o/\mathcal{R})_{H_2O} / T_c] / \sqrt{T_c} = K^{H_2O}$$

$$9: (a_{OH}^{T_L} + \Delta a_{OH}^{T_L} \cdot m_c) / EXP[(H_f^o/\mathcal{R})_{OH} / T_c] = K^{OH}$$

$$10: (a_{NO}^{T_L} + \Delta a_{NO}^{T_L} \cdot m_c) / EXP[(H_f^o/\mathcal{R})_{NO} / T_c] = K^{NO}$$

$$11: (a_H^{T_L} + \Delta a_H^{T_L} \cdot m_c) \cdot \sqrt{T_c} / (\sqrt{p_c}\, EXP[(H_f^o/\mathcal{R})_H / T_c]) = K^H$$

B. continued

12: $\left(a_O^{T_L} + \Delta a_O^{T_L} \cdot m_c\right) \cdot \sqrt{T_c} \Big/ \left(\sqrt{p_c}\, EXP\left[(H_f^\circ/\mathcal{R})_O / T_c\right]\right) = K^O$

13: $\left(a_N^{T_L} + \Delta a_N^{T_L} \cdot m_c\right) \cdot \sqrt{T_c} \Big/ \left(\sqrt{p_c}\, EXP\left[(H_f^\circ/\mathcal{R})_N / T_c\right]\right) = K^N$

14: $K^O \cdot \sqrt{\eta_{O_2}^{EST}} = \eta_O$

15: $K^{NO} \cdot \sqrt{\eta_{O_2}^{EST}} \cdot \sqrt{\eta_{N_2}^{EST}} = \eta_{NO}$

16: $K^N \cdot \sqrt{\eta_{N_2}^{EST}} = \eta_N$

17: $\left(1 + \frac{1}{2} f_c\right) \cdot \left(K^{OH} \cdot \sqrt{\eta_{O_2}} + K^H\right) = A$

18: $\left(1 + f_c\right) \cdot \left(K^{H_2O} \sqrt{\eta_{O_2}} + 1\right) = B$ where $f_c = \dfrac{\nu_C^g}{\nu_{H_2}^g}$

19: $\left\{\sqrt{\left(\frac{A}{2B}\right)^2 + \left(1 - \eta_{N_2} - \eta_{O_2} - \eta_{NO} - \eta_O - \eta_N\right)/B} - \frac{A}{2B}\right\}^2 = \eta_{H_2}$

20: $K^{H_2O} \cdot \eta_{H_2} \cdot \sqrt{\eta_{O_2}} = \eta_{H_2O}$

21: $K^{OH} \cdot \sqrt{\eta_{H_2}} \cdot \sqrt{\eta_{O_2}} = \eta_{OH}$

22: $K^H \cdot \sqrt{\eta_{H_2}} = \eta_H$

23: $\eta_{H_2O} + \eta_{H_2} + \left(\eta_{OH} + \eta_H\right)/2 = \eta_{H_2}^g$

24: $f_c \cdot \eta_{H_2}^g = \eta_C^g$

B. continued

25: $$\gamma_C^g / (1 + K^{CO_2} \cdot \sqrt{\gamma_{O_2}}) = \gamma_{CO}$$

26: $$\gamma_C^g - \gamma_{CO} = \gamma_{CO_2}$$

27: $$\gamma_{CO_2} + \gamma_{O_2} + (\gamma_{CO} + \gamma_{H_2O} + \gamma_{OH} + \gamma_O + \gamma_{NO})/2 = \gamma_{O_2}^g$$

28: $$\gamma_{N_2} + (\gamma_{NO} + \gamma_N)/2 = \gamma_{N_2}^g$$

29: $$\gamma_{N_2}^g / \gamma_{O_2}^g = f_{N_2/O_2}^{calc}$$

30: $$\gamma_{O_2}^g / \gamma_{H_2}^g = f_{O_2}^{calc}$$

31: $$\gamma_{O_2}^{EST(n)} \cdot \left(f_{O_2} / f_{O_2}^{calc} \right)^{X_{O_2}} = \gamma_{O_2}^{EST(n+1)} \text{ where } f_{O_2} = \nu_{O_2}^g / \nu_{H_2}^g$$

32: $$\gamma_{N_2}^{EST(n)} \cdot \left(3.76 / f_{N_2/O_2}^{calc} \right)^{X_{N_2}} = \gamma_{N_2}^{EST(n+1)}$$

At the start of the iteration the value of f_{O_2} is also entered into the memory register for $f_{O_2}^{calc}$ and 3.76 into that for f_{N_2/O_2}^{calc}.

33: If $\left| f_{O_2}^{calc} - f_{O_2} \right| > 10^{-9}$ Go To Line 14

34: If $\left| f_{N_2/O_2}^{calc} - f_{N_2/O_2} \right| > 10^{-9}$ Go To Line 14

F. continued

35: $$\gamma_{H_2}^{g} \cdot \mathcal{M}_{H_2} + \gamma_{O_2}^{g} \cdot \mathcal{M}_{O_2} + \gamma_{C}^{g} \cdot \mathcal{M}_{C} + \gamma_{N_2}^{g} \cdot \mathcal{M}_{N_2} = \mathcal{M}_{CG}^{T_c}$$

36: $$\gamma_{CO_2}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO_2}^{T_L} \cdot m_c\right] + \gamma_{CO}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO} \cdot m_c\right] +$$

$$\gamma_{H_2O}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2O}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2O}^{T_L} \cdot m_c\right] + \gamma_{OH}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{OH}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{OH}^{T_L} \cdot m_c\right] +$$

$$\gamma_{NO}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L} \cdot m_c\right] + \gamma_{O}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L} \cdot m_c\right] +$$

$$\gamma_{H}^{\cdot} \cdot 2.5 + \gamma_{N}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L} \cdot m_c\right] +$$

$$\gamma_{N_2}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L} \cdot m_c\right] + \gamma_{O_2}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} \cdot m_c\right] +$$

$$\gamma_{H_2}^{\cdot}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} \cdot m_c\right] = \left(\frac{h-e_0}{\mathcal{R}T}\right)_{CG}^{T_c}$$

37: $$\left[T_c\left(\frac{h-e_0}{\mathcal{R}T}\right)_{CG}^{T_c} + \gamma_{CO_2}^{\cdot}\left(\frac{H_f^0}{\mathcal{R}}\right)_{CO_2} + \gamma_{CO}^{\cdot}\left(\frac{H_f^0}{\mathcal{R}}\right)_{CO} + \gamma_{H_2O}^{\cdot}\left(\frac{H_f^0}{\mathcal{R}}\right)_{H_2O} +\right.$$

$$+ \gamma_{OH}^{\cdot}\left(\frac{H_f^0}{\mathcal{R}}\right)_{OH} + \gamma_{NO}^{\cdot}\left(\frac{H_f^0}{\mathcal{R}}\right)_{NO} + \gamma_{O}^{\cdot}\left(\frac{H_f^0}{\mathcal{R}}\right)_{O} + \gamma_{H}^{\cdot}\left(\frac{H_f^0}{\mathcal{R}}\right)_{H} +$$

$$\left.\gamma_{N}^{\cdot}\left(\frac{H_f^0}{\mathcal{R}}\right)_{N}\right] \Big/ \mathcal{M}_{CG}^{T_c} = \left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c}$$

P. continued

38: $$\eta'_{CO_2}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{CO_2}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{CO_2}\cdot m_c\right]+\eta'_{CO}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{CO}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{CO}\cdot m_c\right]+$$
$$\eta'_{H_2O}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{H_2O}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{H_2O}\cdot m_c\right]+\eta'_{OH}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{OH}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{OH}\cdot m_c\right]+$$
$$\eta'_{NO}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{NO}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{NO}\cdot m_c\right]+\eta'_{O}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{O}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{O}\cdot m_c\right]+$$
$$\eta'_{N}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{N}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{N}\cdot m_c\right]+\eta'_{O_2}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{O_2}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{O_2}\cdot m_c\right]+$$
$$\eta'_{N_2}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{N_2}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{N_2}\cdot m_c\right]+\eta'_{H_2}\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{H_2}+\Delta\left(\frac{C_p}{\mathcal{R}}\right)^{T_L}_{H_2}\cdot m_c\right]+$$
$$\eta_{H}\cdot 2.5=\left(\frac{C_p}{\mathcal{R}}\right)^{T_c}_{CG}$$

39: $$\left(\frac{C_p}{\mathcal{R}}\right)^{T_c}_{CG}\Big/\left[\left(\frac{C_p}{\mathcal{R}}\right)^{T_c}_{CG}-1\right]=\gamma^{T_c}_{CG}$$

40: $$\left(\frac{h_f}{\mathcal{R}}\right)^{T_c}_{CG}+\frac{1}{2}\gamma^{T_c}_{CG}\cdot T_c\cdot M_c^2\Big/\mathcal{M}^{T_c}_{CG}=\left(\frac{h_f}{\mathcal{R}}\right)^{T_c^\circ(calc)}_{CG}$$

41: IF ABS $\left[\left(\frac{h_f}{\mathcal{R}}\right)^{T_c^\circ}_{CG}-\left(\frac{h_f}{\mathcal{R}}\right)^{T_c^\circ(calc)}_{CG}\right]>10^{-6}$; GTO LINE 5

42: $$u_c=M_c\cdot\sqrt{\gamma^{T_c}_{CG}\cdot\mathcal{R}T_c\Big/\mathcal{M}^{T_c}_{CG}}$$

To calculate T_{DE}, p_{DE}, and u_{DE} zero order estimates of T_{DE} and p_{DE} are needed. These estimates can be obtained from the following equations

43: $$T_{DE}^{EST(0)} = T_{DE}^{o} \Big/ \left(1 + \frac{\gamma-1}{2}\left(M_{DE}^{EST}\right)^2\right)$$

$$p_{DE} = p_{DE}^{o} \left(T_{DE} / T_{DE}^{o}\right)^{\frac{\gamma}{\gamma-1}}$$

where $\gamma \sim 1.3$ and $M_{DE} < M_c$ for subsonic combustion and $M_{DE} > M_c$ for supersonic combustion.

With these estimates the gas speed u_{DE} can be calculated one time from the energy equation (this value will be labelled $u_{DE}^{(E)}$ and then also from an equation which is obtained by combining the momentum and the continuity equation (this value will be labelled $u_{DE}^{(M-C)}$. For the correct values of T_{DE} and p_{DE} these two values are, of course, identical. Therefore, the difference between the two values can be used to calculate improved estimates of the temperature T_{DE} according to the following empirical relationship

44: $$T_{DE}^{EST(n+1)} = T_{DE}^{EST(n)} + x_{T_{DE}} \left(u_{DE}^{(E)} - u_{DE}^{(M-C)}\right)$$

where $x_{T_{DE}} \sim 0.03 \cdot M_\infty + 0.02$

45: $$\left(T_{DE} - T_{L,DE}\right) / 100 = m_{DE}$$

where $T_{L,DE}$ = (integer part of (T_{DE}|100))

46: $$\left(a_{NO}^{T_{L,DE}} + \Delta a_{NO}^{T_{L,DE}} \cdot m_{DE}\right) \Big/ EXP\left(10799/T_{DE}\right) = K^{NO}$$

Since p^{o}_{DE} is the associated isentropic stagnation pressure to p_{DE}, improved values of p_{DE} are obtained by comparing the calculated entropy $\left(\frac{S}{R}\right)^{T_{DE}(calc)}_{eq.air}$ with the known entropy $\left(\frac{S}{R}\right)^{T^{o}_{DE}}_{eq.air}$ according to the following empirical equation:

47: $$p_{DE}^{EST(n+1)} = p_{DE}^{EST(n)} \cdot \left[\left(\frac{S}{R}\right)^{T_{DE}(calc)}_{eq.air} \Big/ \left(\frac{S}{R}\right)^{T^{o}_{DE}}_{eq.air}\right]^{X_p}$$

where $X_p \sim 20$. It is obvious that the value of $\left(\frac{S}{R}\right)^{T^{o}_{DE}}_{eq.air}$ must be entered also into the computer's memory register for $\left(\frac{S}{R}\right)^{T_{DE}(calc)}_{eq.air}$ before the calculations are started.

48: $$\left(a_0^{T_{L,DE}} + \Delta a_0^{T_{L,DE}} \cdot m_{DE}\right)\sqrt{T_{DE}} \Big/ \left[\sqrt{p_{DE}'} \cdot EXP(29685/T_{DE})\right] = K^{O}$$

$$\left(a_N^{T_{L,DE}} + \Delta a_N^{T_{L,DE}} \cdot m_{DE}\right)\sqrt{T_{DE}} \Big/ \left[\sqrt{p_{DE}} \cdot EXP(56613/T_{DE})\right] = K^{N}$$

Enter 0.7 into the computor's memory register for γ_{N_2}

50: $$\gamma_{N_2}^{EST(n)} \cdot \left(3.76 / \xi_{N_2}^{calc}\right)^{X_\gamma} = \gamma_{N_2}^{EST(n+1)}$$

where $X_\gamma \sim 0.3$ Enter 3.76 also into computor's memory for $\xi_{N_2}^{calc}$ before calculations are started.

51: $(K^{NO}\cdot\sqrt{\eta_{N_2}} + K^{O})/2 = C$

52: $K^{N}\cdot\sqrt{\eta_{N_2}} = \eta_{N}$

53: $\left\{\sqrt{C^2+1-\eta_{N_2}-\eta_{N}} - C\right\}^2 = \eta_{O_2}$

54: $K^{O}\sqrt{\eta_{O_2}} = \eta_{O}$

55: $K^{NO}\sqrt{\eta_{O_2}}\cdot\sqrt{\eta_{N_2}} = \eta_{NO}$

56: $\eta_{O_2} + (\eta_{NO}+\eta_{O})/2 = \eta^{g}_{O_2}$

57: $\eta_{N_2} + (\eta_{NO}+\eta_{N})/2 = \eta^{g}_{N_2}$

58: $\eta^{g}_{N_2} / \eta^{g}_{O_2} = f^{calc}_{N_2}$

59: IF ABS$\left(\xi_{N_2}^{calc} - 3.76\right) > 10^{-8}$; GTO LINE 50

60: $\gamma_{N_2}^{g} \cdot \mathcal{M}_{N_2} + \gamma_{O_2}^{g} \cdot \mathcal{M}_{O_2} = \mathcal{M}_{eq.air}^{T_{DE}}$

61: $\gamma_{N_2} \cdot \left[C_{S,N_2}^{T_L,DE} + \Delta C_{S,N_2}^{T_L,DE} \cdot m_{DE}\right] + \gamma_{O_2} \cdot \left[C_{S,O_2}^{T_L,DE} + \Delta C_{S,O_2}^{T_L,DE} \cdot m_{DE}\right] + \gamma_{NO} \cdot \left[C_{S,NO}^{T_L,DE} + \Delta C_{S,NO}^{T_L,DE} \cdot m_{DE}\right] +$

$\gamma_{O} \cdot \left[C_{S,O}^{T_L,DE} + \Delta C_{S,O}^{T_L,DE} \cdot m_{DE}\right] + \gamma_{N} \cdot \left[C_{S,N}^{T_L,DE} + \Delta C_{S,N}^{T_L,DE} \cdot m_{DE}\right] = C_{S,eq.air}^{T_{DE}}$

62: $\gamma_{N_2} \cdot \ln\gamma_{N_2} + \gamma_{O_2} \cdot \ln\gamma_{O_2} + \gamma_{NO} \cdot \ln\gamma_{NO} + \gamma_{O} \cdot \ln\gamma_{O} + \gamma_{N} \ln\gamma_{N} = \left(\sum_i \gamma_i \cdot \ln\gamma_i\right)_{eq.air}^{T_{DE}}$

63: $\left(C_{S,eq.air}^{T_{DE}} \cdot \ln T_{DE} - \left(\sum_i \gamma_i \cdot \ln\gamma_i\right)_{eq.air}^{T_{DE}} - \ln p_{DE}\right) / \mathcal{M}_{eq.air}^{T_{DE}} = \left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_{DE}}$

64: IF ABS$\left[\left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_{DE}} - \left(\frac{S}{\mathcal{R}}\right)_{eq.air}^{T_{DE}^{\circ}}\right] > 10^{-8}$; GTO LINE 47

65: $\gamma_{N_2} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L,DE} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L,DE} \cdot m_{DE}\right] + \gamma_{O_2} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L,DE} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L,DE} \cdot m_{DE}\right] +$

$\gamma_{NO} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L,DE} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L,DE} \cdot m_{DE}\right] + \gamma_{O} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L,DE} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L,DE} \cdot m_{DE}\right] +$

$\gamma_{N} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L,DE} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L,DE} \cdot m_{DE}\right] = \left(\frac{h-e_0}{RT}\right)_{eq.air}^{T_{DE}}$

(continued)

66: $$\left[T_{DE}\cdot\left(\frac{h-e_0}{RT}\right)_{eq.air}^{T_{DE}}+\gamma_{NO}\cdot\left(\frac{H_f^o}{\mathcal{R}}\right)_{NO}+\gamma_O\cdot\left(\frac{H_f^o}{\mathcal{R}}\right)_O+\gamma_N\left(\frac{H_f^o}{\mathcal{R}}\right)_N\right]\Big/\mathfrak{M}_{eq.air}^{T_{DE}}=\left(\frac{h_s}{\mathcal{R}}\right)_{eq.air}^{T_{DE}(calc)}$$

67: $$\sqrt{2\mathcal{R}\left[\left(\frac{h_s}{\mathcal{R}}\right)_{eq.air}^{T_{DE}^o}-\left(\frac{h_s}{\mathcal{R}}\right)_{eq.air}^{T_{DE}(calc)}\right]}=u_{DE}^{(E)}$$

68: $$\left[(1+f)\left(u_c+\frac{\mathcal{R}T_c}{\mathfrak{M}_{CG}^{T_c}\cdot u_c}\right)-f\left(u_f+\frac{\mathcal{R}T_f}{\mathfrak{M}_f\cdot u_f}\cdot g\right)\right]\Big/2=U$$

where g = 0 for liquid fuels and g = 1 for gaseous fuels.

69: $$U\pm\sqrt{U^2-\mathcal{R}T_{DE}\big/\mathfrak{M}_{eq.air}^{T_{DE}}}=u_{DE}^{(M-C)}$$

+ sign for $M_{DE}>1$ and $M_c<1$ or $M_c>1$

− sign for $M_{DE}<1$ and $M_c<1$

70: IF ABS $\left(u_{DE}^{(E)}-u_{DE}^{(M-C)}\right)>10^{-6}$; GTO LINE 44

71: $p_c^{calc} = (1+f)\mathcal{R}T_c \Big/ \left[\mathcal{M}_{CG}^{T_c} \cdot u_c \left(\frac{\mathcal{R}T_{DE}}{\mathcal{M}_{eq.air}^{T_{DE}} u_{DE} \rho_{DE}} + f \frac{101325}{u_f \cdot \rho_f}\right)\right]$

72: IF ABS $(p_c^{calc} - p_c^{EST}) > 10^{-7}$; GTO LINE 4

73: $$\eta_{N_2}\left[\left(\frac{C_p}{\mathcal{R}}\right)_{N_2}^{T_{L,DE}} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{N_2}^{T_{L,DE}} \cdot m_{DE}\right] + \eta_{O_2}\left[\left(\frac{C_p}{\mathcal{R}}\right)_{O_2}^{T_{L,DE}} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{O_2}^{T_{L,DE}} \cdot m_{DE}\right] +$$

$$\eta_{NO}\left[\left(\frac{C_p}{\mathcal{R}}\right)_{NO}^{T_{L,DE}} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{NO}^{T_{L,DE}} \cdot m_{DE}\right] + \eta_{O}\left[\left(\frac{C_p}{\mathcal{R}}\right)_{O}^{T_{L,DE}} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{O}^{T_{L,DE}} \cdot m_{DE}\right] +$$

$$\eta_{N}\left[\left(\frac{C_p}{\mathcal{R}}\right)_{N}^{T_{L,DE}} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{N}^{T_{L,DE}} \cdot m_{DE}\right] = \left(\frac{C_p}{R}\right)_{eq.air}^{T_{DE}}$$

74: $\left(\frac{C_p}{R}\right)_{eq.air}^{T_{DE}} \Big/ \left[\left(\frac{C_p}{R}\right)_{eq.air}^{T_{DE}} - 1\right] = \gamma_{eq.air}^{T_{DE}}$

75: $M_{DE} = u_{DE} \Big/ \sqrt{\gamma_{eq.air}^{T_{DE}} \mathcal{R} T_{DE} \big/ \mathcal{M}_{eq.air}^{T_{DE}}}$

END

CALCULATION OF COMBUSTION CHAMBER EXIT CONDITIONS (T_c, u_c, p_c) OF A RAMJET FOR A SPECIFIED DIFFUSER EXIT SPEED (u_{DE}) AND $A_c = A_{DE} + A_f$

$$0: \left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^\circ} = \left[T_\infty\left(\frac{h_f}{RT}\right)_{air}^{T_\infty} \Big/ \mathcal{M}_{air} + \frac{u_\infty^2}{2\mathcal{R}} + f\left\{T_f\left(\frac{h_f}{RT}\right)_f^{T_f} \Big/ \mathcal{M}_f + \frac{u_f^2}{2\mathcal{R}}\right\}\right] \Big/ (1+f)$$

$$1: u_{c,max}^{(M\text{-}C)} = \left[u_{DE} + \frac{\mathcal{R}T_{DE}}{u_{DE}\,\mathcal{M}_{eq\,air}^{T_{DE}}} + f\left\{u_f + g\frac{\mathcal{R}\,T_f}{u_f\,\mathcal{M}_f}\right\}\right] \Big/ (1+f)$$

$g = 0$ when fuel enters combustion chamber as a liquid

$g = 1$ for all gaseous fuels

$$2: \gamma_{N_2}^{EST(0)} = 6.75\, f_{O_2} \big/ (1 + 9.52\, f_{O_2})$$

$$3: p_c^{EST(0)} = p_{DE}^{\circ} \cdot x \qquad 0.6\,(\text{high } M_{DE}) \le x \le 0.9\,(\text{low } M_{DE})$$

$$4: T_c^{EST(0)} = T_\infty^\circ + f\left|\Delta h_{comb,f}^{T_f}\right| \sqrt{T_\infty / T_\infty^\circ} \Big/ (4.8\, R_{air})$$

$$5: T_c^{EST(0)} = T_c^{EST(0)} - 50$$

$$6: p_c^{EST(n+1)} = p_c^{EST(n)} + x_p\left(p_c^{calc(n)} - p_c^{EST(n)}\right)$$

$$7: T_c^{EST(n+1)} = T_c^{EST(n)} + x_T\left(u_c^{(E)} - u_c^{(M\text{-}C)}\right)$$

$$8: m = (T_c - T_L)/100$$

where again $T_L = 100 \cdot (\text{INTEGER PART OF}(T_c/100))$

$$9:\left(a^{T_L}_{CO_2}+\Delta a^{T_L}_{CO_2}\cdot m\right)\cdot T_c^{.125}\,EXP\left\{\left[\left(\frac{H_c^\circ}{R}\right)_{CO}-\left(\frac{H_c^\circ}{R}\right)_{CO_2}\right]\Big/T_c\right\}\sqrt{p_c}=K^{CO_2}$$

$$10:\left(a^{T_L}_{H_2O}+\Delta a^{T_L}_{H_2O}\cdot m\right)\cdot\sqrt{p_c}\;EXP\left[-\left(\frac{H_c^\circ}{R}\right)_{H_2O}\Big/T_c\right]\Big/\sqrt{T_c}=K^{H_2O}$$

$$11:\left(a^{T_L}_{OH}+\Delta a^{T_L}_{OH}\cdot m\right)\Big/EXP\left[\left(\frac{H_c^\circ}{R}\right)_{OH}\Big/T_c\right]=K^{OH}$$

$$12:\left(a^{T_L}_{NO}+\Delta a^{T_L}_{NO}\cdot m\right)\Big/EXP\left[\left(\frac{H_c^\circ}{R}\right)_{NO}\Big/T_c\right]=K^{NO}$$

$$13:\left(a^{T_L}_{H}+\Delta a^{T_L}_{H}\cdot m\right)\cdot\sqrt{T_c}\Big/\left(\sqrt{p_c}\;EXP\left[\left(\frac{H_c^\circ}{R}\right)_{H}\Big/T_c\right]\right)=K^{H}$$

$$14:\left(a^{T_L}_{O}+\Delta a^{T_L}_{O}\cdot m\right)\cdot\sqrt{T_c}\Big/\left(\sqrt{p_c}\;EXP\left[\left(\frac{H_c^\circ}{R}\right)_{O}\Big/T_c\right]\right)=K^{O}$$

$$15:\left(a^{T_L}_{N}+\Delta a^{T_L}_{N}\cdot m\right)\sqrt{T_c}\Big/\left(\sqrt{p_c}\;EXP\left[\left(\frac{H_c}{R}\right)_{N}\Big/T_c\right]\right)=K^{N}$$

$$16:\quad K^{O}\cdot\sqrt{\eta_{O_2}^{EST}}=\eta_O$$

$$17:\quad K^{NO}\cdot\sqrt{\eta_{O_2}^{EST}}\cdot\sqrt{\eta_{N_2}^{EST}}=\eta_{NO}$$

$$18:\quad K^{N}\cdot\sqrt{\eta_{N_2}^{EST}}=\eta_N$$

$$19:\quad\left(1+\tfrac{1}{2}\xi_c\right)\cdot\left(K^{OH}\cdot\sqrt{\eta_{O_2}}+K^{H}\right)=A$$

$$20:\quad\left(1+\xi_c\right)\cdot\left(K^{H_2O}\cdot\sqrt{\eta_{O_2}}+1\right)=B$$

$$21: \left\{\sqrt{\left(\frac{A}{2B}\right)^2 + \left(1 - \eta_{N_2} - \eta_{O_2} - \eta_{NO} - \eta_O - \eta_N\right)/B} - \frac{A}{2B}\right\}^2 = \eta_{H_2}$$

$$22: K^{H_2O} \cdot \eta_{H_2} \cdot \sqrt{\eta_{O_2}^{EST}} = \eta_{H_2O}$$

$$23: K^{OH} \cdot \sqrt{\eta_{H_2}} \cdot \sqrt{\eta_{O_2}^{EST}} = \eta_{OH}$$

$$24: K^{H} \cdot \sqrt{\eta_{H_2}} = \eta_H$$

$$25: \eta_{H_2O} + \eta_{H_2} + (\eta_{OH} + \eta_H)/2 = \eta_{H_2}^{g}$$

$$26: \xi_C \cdot \eta_{H_2}^{g} = \eta_C^{g}$$

$$27: \eta_C^{g} / (1 + K^{CO_2} \cdot \sqrt{\eta_{O_2}^{EST}}) = \eta_{CO}$$

$$28: \eta_C^{g} - \eta_{CO} = \eta_{CO_2}$$

$$29: \eta_{CO_2} + \eta_{O_2} + (\eta_{CO} + \eta_{H_2O} + \eta_{OH} + \eta_O + \eta_{NO})/2 = \eta_{O_2}^{g}$$

$$30: \eta_{N_2} + (\eta_{NO} + \eta_N)/2 = \eta_{N_2}^{g}$$

$$31: \eta_{N_2}^{g} / \eta_{O_2}^{g} = \xi_{N_2/O_2}^{calc}$$

$$32:\ \eta^{g}_{O_2} / \eta^{g}_{H_2} = \xi^{calc}_{O_2}$$

$$33:\ \eta^{EST(n)}_{O_2} \cdot \left(\xi_{O_2} / \xi^{calc}_{O_2} \right)^{X_{O_2}} = \eta^{EST(n+1)}_{O_2}$$

$$34:\ \eta^{EST(n)}_{N_2} \cdot \left(3.76 / \xi^{calc}_{N_2/O_2} \right)^{X_{N_2}} = \eta^{EST(n+1)}_{N_2}$$

At the start of the calculations the value of ξ_{O_2} is also entered into the memory register for $\xi^{calc}_{O_2}$ and 3.76 into that for $\xi^{calc}_{N_2/O_2}$.

$$35:\ \text{IF ABS}\left(\xi^{calc}_{O_2} - \xi_{O_2}\right) > 10^{-9};\ \text{GTO LINE 16}$$

$$36:\ \text{IF ABS}\left(\xi^{calc}_{N_2/O_2} - 3.76\right) > 10^{-9};\ \text{GTO LINE 16}$$

$$37:\ \eta^{g}_{H_2} \cdot \mathcal{M}_{H_2} + \eta^{g}_{O_2} \cdot \mathcal{M}_{O_2} + \eta^{g}_{C} \cdot \mathcal{M}_{C} + \eta^{g}_{N_2} \cdot \mathcal{M}_{N_2} = \mathcal{M}^{T_c}_{CG}$$

$$38:\ \eta_{CO_2} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{CO_2} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{CO_2} \cdot m \right] + \eta_{CO} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{CO} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO} \cdot m \right] +$$

$$\eta_{H_2O} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{H_2O} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{H_2O} \cdot m \right] + \eta_{OH} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{OH} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{OH} \cdot m \right] +$$

$$\eta_{NO} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{NO} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{NO} \cdot m \right] + \eta_{O} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{O} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{O} \cdot m \right] +$$

$$\eta_{H} \cdot 2.5 + \eta_{N} \cdot \left[\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{N} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)^{T_L}_{N} \cdot m \right] +$$

$$\gamma_{N_2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L}+\Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L}\cdot m\right]+\gamma_{O_2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L}+\Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L}\cdot m\right]+$$

$$\gamma_{H_2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L}+\Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}\cdot m\right]=\left(\frac{h-e_0}{RT}\right)_{CG}^{T_c}$$

39: $$\left[T_c\left(\frac{h-e_0}{RT}\right)_{CG}^{T_c}+\gamma_{CO_2}\left(\frac{H_f^\circ}{\mathcal{R}}\right)_{CO_2}+\gamma_{CO}\left(\frac{H_f^\circ}{\mathcal{R}}\right)_{CO}+\gamma_{H_2O}\left(\frac{H_f^\circ}{\mathcal{R}}\right)_{H_2O}+\right.$$

$$\gamma_{OH}\left(\frac{H_f^\circ}{\mathcal{R}}\right)_{OH}+\gamma_{NO}\left(\frac{H_f^\circ}{\mathcal{R}}\right)_{NO}+\gamma_{O}\left(\frac{H_f^\circ}{\mathcal{R}}\right)_{O}+\gamma_{H}\left(\frac{H_f^\circ}{\mathcal{R}}\right)_{H}+$$

$$\left.\gamma_{N}\left(\frac{H_f^\circ}{\mathcal{R}}\right)_{N}\right]\Big/\mathcal{M}_{CG}^{T_c}=\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c\,(calc)}$$

40: IF $\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c\,(calc)}>\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^\circ}$; GTO LINE 5

41: $$\sqrt{2\mathcal{R}\left[\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^\circ}-\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c(calc)}\right]}=u_C^{(E)}$$

42: IF $\sqrt{\mathcal{R}T_c/\mathcal{M}_{CG}^{T_c}}>u_{c,max}^{(M-C)}/2$; GTO LINE 5

43: $$u_{c,max}^{(M-C)}/2-\sqrt{\left(u_{c,max}^{(M-C)}/2\right)^2-\mathcal{R}T_c/\mathcal{M}_{CG}^{T_c}}=u_c^{(M-C)}$$

44: IF ABS$\left(u_c^{(E)}-u_c^{(M-C)}\right)>10^{-6}$; GTO LINE 7

45: $$p_c^{calc}=(1+f)\mathcal{R}T_c\Big/\left(\mathcal{M}_c^{CG}u_c\left[101325\cdot f/\rho_f u_f+\mathcal{R}T_{DE}/\mathcal{M}_{eq.air}^{T_{DE}}u_{DE}\rho_{DE}\right]\right)$$

46: IF ABS$\left(p_c^{calc}-p_c^{EST}\right)>10^{-7}$; GTO LINE 6

$$47: \quad \eta_{CO_2} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{CO_2}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{CO_2}^{T_L} \cdot m \right] + \eta_{CO} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{CO}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{CO}^{T_L} \cdot m \right] +$$

$$\eta_{H_2O} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{H_2O}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{H_2O}^{T_L} \cdot m \right] + \eta_{OH} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{OH}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{OH}^{T_L} \cdot m \right] +$$

$$\eta_{NO} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{NO}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{NO}^{T_L} \cdot m \right] + \eta_{O} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{O}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{O}^{T_L} \cdot m \right] +$$

$$\eta_{H} \cdot 2.5 + \eta_{N} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{N}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{N}^{T_L} \cdot m \right] +$$

$$\eta_{O_2} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{O_2}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{O_2}^{T_L} \cdot m \right] + \eta_{N_2} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{N_2}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{N_2}^{T_L} \cdot m \right] +$$

$$\eta_{H_2} \cdot \left[\left(\frac{C_p}{\mathcal{R}}\right)_{H_2}^{T_L} + \Delta\left(\frac{C_p}{\mathcal{R}}\right)_{H_2}^{T_L} \cdot m \right] = \left(\frac{C_p}{\mathcal{R}}\right)_{CG}^{T_C}$$

$$48: \quad \left(\frac{C_p}{\mathcal{R}}\right)_{CG}^{T_C} \Big/ \left[\left(\frac{C_p}{\mathcal{R}}\right)_{CG}^{T_C} - 1 \right] = \gamma_{CG}^{T_C}$$

$$49: \quad M_C = u_C \Big/ \sqrt{\gamma_{CG}^{T_C} \mathcal{R} T_C \big/ \mathcal{M}_{CG}^{T_C}}$$

END

C. CALCULATION OF EXHAUST NOZZLE EXIT CONDITIONS AND ENGINE PERFORMANCE PARAMETERS.

From a theoretical point of view the optimum performance of the exhaust nozzle of any jet engine is obtained when it is designed to expand the propellant gas to the pressure of the ambient atmosphere (e.g. $p_e=p_\infty$). However, for high pressure ratios ($\frac{p_c^o}{p_\infty}$) such an expansion may lead to extremely large exit areas and thus long and heavy exhaust nozzles so that the actual performance of the engine may be reduced because of the extra weight and drag of such large nozzles. Since it was the objective of this study to determine the optimum thermodynamic performance of the ramjet engine, ideal and isentropic expansion was assumed. For any isentropic expansion the static temperature at the nozzle exit can be calculated readily from the entropy equation. For a calorically perfect gas we have

$$T_e = T_c \cdot (p_e/p_c)^{(\gamma-1)/\gamma}$$

where T_e and p_e have been calculated previously and p_e is specified. Since the specific heats of any combustion gas in the range from T_c down to T_e vary greatly with temperature, this isentropic temperature-pressure relationship can be used only as a rough estimate of the exit temperature (with $\gamma \sim 1.3$). For rigorous calculations the entropy equation has to be used in the general form

$$\left(\frac{S}{R}\right)_{CG}^{T_e} = \left(c_{s,CG}^{T_e} \cdot \ln T_e - \left(\sum_i \gamma_i \ln \gamma_i\right)_{CG}^{T_e} - \ln p_e\right) \Big/ M_{CG}^{T_e} = \left(\frac{S}{R}\right)_{CG}^{T_c}$$

The only unknown in this equation is T_e. Obviously, it has to be calculated by an iterative procedure since $c_{s,CG}^{T_e} = \sum_i \gamma_i c_{s,i}^{T_e}$ is a function of temperature and when T_e is above 1500K even the temperature effect on the γ_i may have to be considered. Since in some cases the exit temperature is higher than 1500 K, all calculations were made by including the chemical equilibria. If for low values of T_e the extremely low numbers for some of the γ_i stop the computer because of an underflow condition (or overflow if reciprocal values appear), the appropriate instructions for

by-passing this impasse have to be incorporated into the program. Although the calculations are similar to those in the previous sections, the equations are given here as they apply to the calculation of the exhaust nozzle performance. Before the calculations are started enter 0.7 into the memory register for γ_{N_2}, 0.01 into that for γ_{O_2} the value of $\left(\frac{S}{R}\right)^{T_c}_{CG}$ into both the register for $\left(\frac{S}{R}\right)^{T_c}_{CG}$ and that for $\left(\frac{S}{R}\right)^{T_e}_{CG}$, also the value of ξ_{O_2} into the memory for ξ_{O_2} and that for $\xi^{calc}_{O_2}$ and finally 3.76 into the memory for $\xi^{calc}_{N_2/O_2}$.

$$0: \; T_e^{EST(0)} = T_c \cdot (p_e / p_c)^{\frac{\gamma}{\gamma-1}} \qquad \gamma \sim 1.3$$

$$1: \; T_e^{EST(n+1)} = T_e^{EST(n)} \cdot \left[\left(\frac{S}{R}\right)_{CG}^{T_c} \Big/ \left(\frac{S}{R}\right)_{CG}^{T_e^{EST(n)}} \right]$$

$$2: \; (T_e - T_L)/100 = m$$

$$3: \; T_L = 100 \cdot (\text{INTEGER PART OF } (T_e/100))$$

$$4: \; K^{CO_2} = (a_{CO_2}^{T_L} + \Delta a_{CO_2}^{T_L} \cdot m) \cdot T_e^{.125} \, EXP(33598/T_e) \cdot \sqrt{p_e}$$

$$5: \; K^{H_2O} = (a_{H_2O}^{T_L} + \Delta a_{H_2O}^{T_L} \cdot m) \cdot EXP(28736/T_e) \cdot \sqrt{p_e} / \sqrt{T_e}$$

$$6: \; K^{OH} = (a_{OH}^{T_L} + \Delta a_{OH}^{T_L} \cdot m) / EXP(4675/T_e)$$

$$7: \; K^{NO} = (a_{NO}^{T_L} + \Delta a_{NO}^{T_L} \cdot m) / EXP(10799/T_e)$$

$$8: \; K^{O} = (a_{O}^{T_L} + \Delta a_{O}^{T_L}) \cdot \sqrt{T_e} / (\sqrt{p_e} \, EXP(29685/T_e))$$

$$9: \; K^{H} = (a_{H}^{T_L} + \Delta a_{H}^{T_L}) \cdot \sqrt{T_e} / (\sqrt{p_e} \, EXP(25982/T_e))$$

$$10: \; K^{N} = (a_{N}^{T_L} + \Delta a_{N}^{T_L}) \cdot \sqrt{T_e} / (\sqrt{p_e} \, EXP(56613/T_e))$$

$$11: \; \eta_{O_2}^{EST(n+1)} = \eta_{O_2}^{EST(n)} \cdot (f_{O_2} / f_{O_2}^{calc})^{x_{O_2}} \qquad x_{O_2} \sim 0.$$

$$12: \; \eta_{N_2}^{EST(n+1)} = \eta_{N_2}^{EST(n)} \cdot (3.76 / f_{N_2/O_2}^{calc})^{x_{N_2}} \qquad x_{N_2} \sim 0$$

$$13: \; \eta_O = K^O \cdot \sqrt{\eta_{O_2}^{EST}}$$

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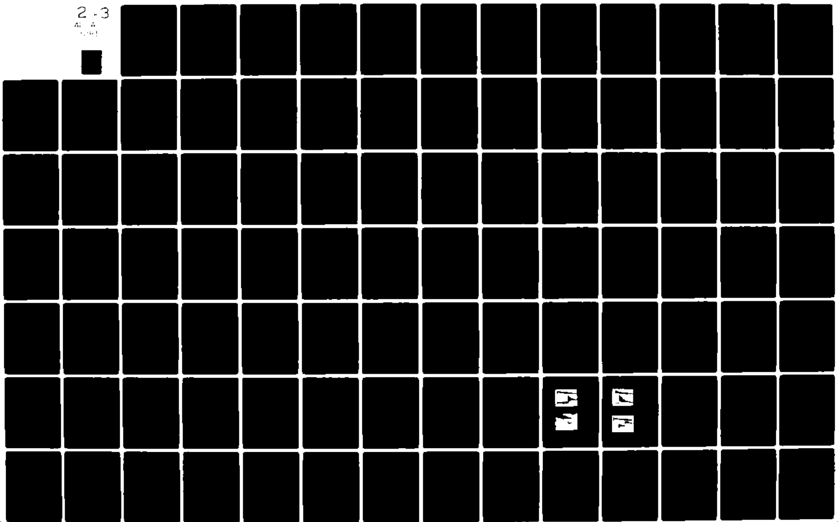
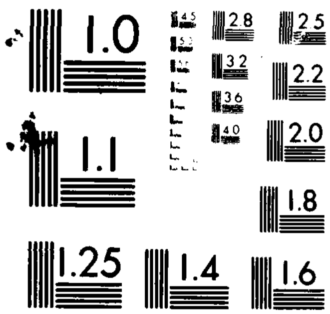




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

14: $\eta_{NO} = K^{NO} \cdot \sqrt{\hat{\eta}_{O_2}^{EST}} \cdot \sqrt{\hat{\eta}_{N_2}^{EST}}$

15: $\eta_{N} = K^{N} \cdot \sqrt{\hat{\eta}_{N_2}^{EST}}$

16: $A = (1 + \xi_c/2) \cdot (K^{OH} \cdot \sqrt{\hat{\eta}_{O_2}^{EST}} + K^{H})$

17: $B = (1 + \xi_c) \cdot (K^{H_2O} \cdot \sqrt{\hat{\eta}_{O_2}^{EST}} + 1)$

18: $\eta_{H_2} = \left\{ \sqrt{\left(\frac{A}{2B}\right)^2 + (1 - \hat{\eta}_{N_2}^{EST} - \eta_{O_2}^{EST} - \eta_{NO} - \eta_{O} - \eta_{N})/B} - \frac{A}{2B} \right\}^2$

19: $\eta_{H_2O} = K^{H_2O} \cdot \hat{\eta}_{H_2} \cdot \sqrt{\hat{\eta}_{O_2}^{EST}}$

20: $\eta_{OH} = K^{OH} \cdot \sqrt{\eta_{H_2}} \cdot \sqrt{\eta_{O_2}^{EST}}$

21: $\eta_{H} = K^{H} \cdot \sqrt{\eta_{H_2}}$

22: $\eta_{H_2}^{g} = \eta_{H_2O} + \eta_{H_2} + (\eta_{OH} + \eta_{H})/2$

23: $\eta_{C}^{g} = \xi_c \cdot \eta_{H_2}^{g}$

24: $\eta_{CO} = \eta_{C}^{g} / (1 + K^{CO_2} \cdot \sqrt{\hat{\eta}_{O_2}^{EST}})$

25: $\eta_{CO_2} = \eta_{C}^{g} - \eta_{CO}$

$$26: \eta_{O_2}^{g} = \eta_{CO_2} + \eta_{O_2} + (\eta_{CO} + \eta_{H_2O} + \eta_{OH} + \eta_{NO} + \eta_{O})/2$$

$$27: \eta_{N_2}^{g} = \eta_{N_2} + (\eta_{NO} + \eta_{N})/2$$

$$28: \xi_{N_2/O_2}^{calc} = \eta_{N_2}^{g} / \eta_{O_2}^{g}$$

$$29: \xi_{O_2}^{calc} = \eta_{O_2}^{g} / \eta_{H_2}^{g}$$

30: IF ABS $(\xi_{O_2} - \xi_{O_2}^{calc}) > 10^{-8}$; GTO LINE 11

31: IF ABS$(3.76 - \xi_{N_2/O_2}) > 10^{-8}$; GTO LINE 11

$$32: \eta_{CO_2} \cdot \left[c_{s,CO_2}^{T_L} + \Delta c_{s,CO_2}^{T_L} \cdot m \right] + \eta_{CO} \cdot \left[c_{s,CO}^{T_L} + \Delta c_{s,CO}^{T_L} \cdot m \right] +$$

$$\eta_{H_2O} \cdot \left[c_{s,H_2O}^{T_L} + \Delta c_{s,H_2O}^{T_L} \cdot m \right] + \eta_{OH} \cdot \left[c_{s,OH}^{T_L} + \Delta c_{s,OH}^{T_L} \cdot m \right] +$$

$$\eta_{NO} \cdot \left[c_{s,NO}^{T_L} + \Delta c_{s,NO}^{T_L} \cdot m \right] + \eta_{N_2} \cdot \left[c_{s,N_2}^{T_L} + \Delta c_{s,N_2}^{T_L} \cdot m \right] +$$

$$\eta_{O_2} \cdot \left[c_{s,O_2}^{T_L} + \Delta c_{s,O_2}^{T_L} \cdot m \right] + \eta_{H_2} \cdot \left[c_{s,H_2}^{T_L} + \Delta c_{s,H_2}^{T_L} \cdot m \right] +$$

$$\eta_{O} \cdot \left[c_{s,O}^{T_L} + \Delta c_{s,O}^{T_L} \cdot m \right] + \eta_{H} \cdot \left[c_{s,H}^{T_L} + \Delta c_{s,H}^{T_L} \cdot m \right] +$$

$$\eta_{N} \cdot \left[c_{s,N}^{T_L} + \Delta c_{s,N}^{T_L} \cdot m \right] = c_{s,CG}^{T_e}$$

$$33:\ \dot{\gamma}_{CO_2} \ln\gamma_{CO_2} + \dot{\gamma}_{CO} \ln\gamma_{CO} + \dot{\gamma}_{H_2O} \ln\gamma_{H_2O} + \dot{\gamma}_{OH} \ln\gamma_{OH} +$$

$$\dot{\gamma}_{NO} \ln\gamma_{NO} + \dot{\gamma}_{O_2} \ln\gamma_{O_2} + \dot{\gamma}_{N_2} \ln\gamma_{N_2} + \dot{\gamma}_{H_2} \ln\gamma_{H_2} +$$

$$\dot{\gamma}_{O} \ln\gamma_{O} + \dot{\gamma}_{H} \ln\gamma_{H} + \dot{\gamma}_{N} \ln\gamma_{N} = \left(\sum_i \gamma_i \ln\gamma_i\right)_{CG}^{T_e}$$

$$34:\ \dot{\gamma}_{N_2}^{g} \mathcal{M}_{N_2} + \dot{\gamma}_{O_2}^{g} \mathcal{M}_{O_2} + \dot{\gamma}_{H_2}^{g} \mathcal{M}_{H_2} + \gamma_{C}^{g} \mathcal{M}_{C} = \mathcal{M}_{CG}^{T_e}$$

$$35:\ \left(c_{s,CG}^{T_e} \cdot \ln T_e - \left(\sum_i \gamma_i \ln\gamma_i\right)_{CG}^{T_e} - \ln p_e\right) \Big/ \mathcal{M}_{CG}^{T_e} = \left(\frac{s}{\mathcal{R}}\right)_{CG}^{T_e}$$

$$36:\ \text{IF ABS}\left[\left(\frac{s}{\mathcal{R}}\right)_{CG}^{T_e} - \left(\frac{s}{\mathcal{R}}\right)_{CG}^{T_c}\right] > 10^{-8} :\ \text{GTO LINE } 1$$

$$37:\ \dot{\gamma}_{CO_2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO_2}^{T_L} \cdot m\right] + \dot{\gamma}_{CO}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{CO}^{T_L} \cdot m\right] +$$

$$\dot{\gamma}_{H_2O}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2O}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2O}^{T_L} \cdot m\right] + \dot{\gamma}_{OH}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{OH}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{OH}^{T_L} \cdot m\right] +$$

$$\dot{\gamma}_{NO}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{NO}^{T_L} \cdot m\right] + \dot{\gamma}_{N_2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N_2}^{T_L} \cdot m\right] +$$

$$\dot{\gamma}_{O_2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O_2}^{T_L} \cdot m\right] + \gamma_{H_2}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{H_2}^{T_L} \cdot m\right] +$$

$$\dot{\gamma}_{O}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{O}^{T_L} \cdot m\right] + \dot{\gamma}_{N}\left[\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L} + \Delta\left(\frac{H-E_0}{\mathcal{R}T}\right)_{N}^{T_L} \cdot m\right] +$$

$$\dot{\gamma}_{H} \cdot 2.5 = \left(\frac{h-e_0}{RT}\right)_{CG}^{T_e}$$

$$38: \left[T_e \cdot \left(\frac{h - e_0}{RT} \right)_{CG}^{T_e} + \eta_{CO_2} \cdot \left(\frac{H_f^\circ}{\mathcal{R}} \right)_{CO_2} + \eta_{CO} \cdot \left(\frac{H_f^\circ}{\mathcal{R}} \right)_{CO} + \eta_{H_2O} \left(\frac{H_f^\circ}{\mathcal{R}} \right)_{H_2O} + \eta_{OH} \cdot \left(\frac{H_f^\circ}{\mathcal{R}} \right)_{OH} + \eta_{NO} \cdot \left(\frac{H_f^\circ}{\mathcal{R}} \right)_{NO} + \eta_{O} \cdot \left(\frac{H_f^\circ}{\mathcal{R}} \right)_{O} + \eta_{H} \cdot \left(\frac{H_f^\circ}{\mathcal{R}} \right)_{H} + \eta_{N} \cdot \left(\frac{H_f^\circ}{\mathcal{R}} \right)_{N} \right] \Big/ \mathcal{M}_{CG}^{T_e} = \left(\frac{h_f}{\mathcal{R}} \right)_{CG}^{T_e}$$

$$39: \quad u_e = \sqrt{u_c^2 + 2\mathcal{R}\left[\left(\frac{h_f}{\mathcal{R}} \right)_{CG}^{T_c} - \left(\frac{h_f}{\mathcal{R}} \right)_{CG}^{T_e} \right]} \quad \left[\frac{m}{s} \right]$$

$$40: \quad F_s = (1+f) \cdot u_e - u_\infty \quad \left[\frac{m}{s} \right]$$

$$41: \quad F_{sfc} = \frac{3600 \cdot f}{F_s} \quad \left[\frac{\text{kg FUEL/hour}}{N} \right]$$

$$42: \quad \frac{A_e}{\dot{m}_{air}} = (1+f) \cdot \mathcal{R}^* T_e \Big/ \left(p_e \cdot u_e \cdot \mathcal{M}_{CG}^{T_e} \right)$$

$$43: \quad \eta_{TH} = \left[(1+f) \cdot u_e^2 - u_\infty^2 \right] \Big/ \left(2 \cdot f \cdot |\Delta h_{comb, FUEL}^{T_f}| \right)$$

$$44: \quad \eta_P = 2 \cdot \left[(1+f) - \frac{u_\infty}{u_e} \right] \Big/ \left[(1+f) \frac{u_e}{u_\infty} - (1-f) \frac{u_\infty}{u_e} \right]$$

$$45: \quad \eta_O = F_s \cdot u_\infty \Big/ \left(f \cdot |\Delta h_{comb, FUEL}^{T_f}| \right)$$

46: END

D. RAMJET RESULTS AND CONCLUSIONS

The results of these calculations show that specific thrust and thrust specific fuel consumption of a ramjet flying at a given speed do not vary more than a few percent over an altitude range of between 5000 and 30000 meters (see Figures 37 & 38). The data show that the performance decreases as the temperature of the atmospheric air increases but it increases as the atmospheric pressure increases (see Tables 68 to 70).

Although isentropic diffusion is highly desireable from the viewpoint of maximizing the thermodynamic efficiency of the engine, at high flight Mach numbers the resulting pressures within the engine become impossible unless the supersonic combustion mode is employed. The supersonic combustion mode does allow for lower pressures around which the engine can be designed but in general there is a decrease in performance (see Tables 42,44,46,48 etc.).

As expected, the thermodynamic efficiency of a ramjet with an isentropic diffuser increases with flight Mach number, whereas that of a simple subsonic diffuser with a normal shock wave at the inlet first increases, reaches a maximum between $M_\infty = 4$ and $M_\infty = 5$ and then decreases rapidly as flight Mach number continues to increase. Figure 35 demonstrates this. However, in both cases the performance of the engine has a maximum between $M_\infty = 3$ and $M_\infty = 4$ for the isentropic diffusion process and at $M_\infty = 2.5$ for the case where a normal shock wave exists at the diffuser inlet.

Although the overall efficiency of an ideal ramjet increases with flight Mach number (see Figure 36), this

D. continued

fact is of no practical value because of the impossibly high internal pressures involved at the very high flight Mach numbers. Also, the diffuser inlet and exhaust nozzle exit areas would be much too large (see Tables 63 to 65).

In addition, the calculations show that when hydrogen fuel is injected as a gas (e.g. after being used as a coolant in the liquid state) the performance is higher than when the hydrogen is injected as a liquid (see Figure 33). However, both cases using hydrogen as a fuel show greater performance than if propane is used as a fuel. Also, the thrust specific fuel consumption of a ramjet using hydrogen as a fuel is almost twice as good as a ramjet using propane (see Figure 34). However, due to the low density of hydrogen, large fuel tanks may be required. In fact, the volume of hydrogen required to obtain the same amount of energy as a volume of propane is nearly triple that of the propane.

In conclusion, it can be stated that the most practical range of speeds for ramjets lies between $M_\infty = 2$ and $M_\infty = 7$ and that the optimum flight Mach number is approximately $M_\infty = 4$.

Table 1
Wave Velocities And Pressures For
$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$ At
.5 Atm. Initial Pressure And
300 K Initial Temperature

Wave Velocities, w_1 (m/s)

D.F.I.* (m)	Run #1	Run #2	Run #3
2.41	797	797	797
3.94	1022	954	906
4.53	2019	1695	1907
4.84	2418	2262	2597
5.77	2333	2260	2260
6.23	1663	1839	1829

Wave Pressures, p_3 (Atm.)

D.F.I.* (m)	Run #1	Run #2	Run #3
2.41	1.51	1.51	1.51
3.94	8.80	10.72	11.44
4.53	23.34	23.10	23.34
4.84	23.83	24.07	19.74
5.77	16.13	22.14	23.58
6.23	10.33	10.33	9.41

*D.F.I. is the distance from the ignitor to each of the listed transducer locations

Table 2
Wave Velocities And Pressures For
$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$ At
1 Atm. Initial Pressure And
300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	162	162	162
2.41	941	941	941
3.01	1360	1360	1580
3.31	1613	1741	1613
3.94	2511	2651	2511
4.53	2162	2179	2214
4.84	2191	2125	2093
5.77	2169	2126	2105
6.23	2044	2007	2032

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	11.06	11.06	14.07
2.41	12.06	11.55	10.55
3.01	28.65	28.65	26.35
3.31	24.04	28.65	28.65
3.94	28.05	29.21	28.65
4.53	25.05	23.12	20.48
4.84	20.00	19.76	23.12
5.77	23.36	22.16	22.64
6.23	17.59	16.67	16.36

*D.F.I. is the distance from the ignitor to each of the listed transducer locations

Table 3
Wave Velocities And Pressures For
$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$ At
2 Atm. Initial Pressure And
300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.80	1198	1016	986
2.41	1279	1111	1210
3.01	2066	1852	1919
3.31	2286	2286	2385
3.94	2602	2309	2468
4.53	2179	2179	2179
4.84	2191	2191	2191
5.77	2147	2213	2236
6.23	2057	2057	2057

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
2.41	23.12	26.13	24.40
3.01	29.65	29.65	30.42
3.31	28.89	28.12	29.65
3.94	30.25	29.65	29.65
4.53	29.65	30.25	29.65
4.84	29.65	29.65	29.65
5.77	29.65	30.86	30.86
6.23	30.42	31.19	31.57

*D.F.I. is the distance from the ignitor to each of the listed transducer locations

Table 4
Wave Velocities & Pressures For
$\frac{1}{2} O_2 + H_2 + N_2$ At
.5 Atm. Initial Pressure
And 300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run # 1	Run # 2	Run # 3
1.80	63	63	63
3.01	350	350	343
3.31	588	599	599
4.53	2324	2324	2324
4.84	2891	2942	2916
5.77	2520	2535	2504
6.23	2339	2312	2286

Wave Pressures, p_3 (Atm.)			
D.F.I.*	Run # 1	Run # 2	Run # 3
1.80	7.9	8.5	8.5
3.01	8.1	8.5	8.1
3.31	10.2	12.1	10.5
4.53	34.6	36.5	36.5
4.84	28.1	33.9	33.9
5.77	28.1	31.5	36.5
6.23	25.0	25.3	25.7

* D.F.I. is the distance from the ignitor to each of the listed transducer positions

Table 5
Wave Velocities & Pressures For
$\frac{1}{2}\ O_2 + H_2 + N_2$ At
1 Atm. Initial Pressure
And 300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.80	633	639	645
3.01	1799	1705	2020
3.31	3193	3193	3048
3.94	2852	2913	2883
4.53	2794	2736	2736
4.84	2580	2683	2580
5.77	2474	2445	2460

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.80	1.8	2.0	1.9
3.01	37.0	47.4	48.6
3.31	42.3	43.5	43.0
3.94	44.6	47.3	46.5
4.53	38.3	37.5	38.0
4.84	25.5	28.0	28.8
5.77	22.8	22.5	23.5

* D.F.I. is the distance from the ignitor to each of the listed transducer positions

Table 6

Wave Velocities & Pressures For

$\frac{1}{2} O_2 + H_2 + N_2$ At

2 Atm. Initial Pressure

And 300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.80	664	658	658
2.41	1342	1356	1279
3.01	2388	2388	2736
3.31	2794	2794	2682
3.94	2535	2489	2583
4.53	2501	2501	2501
4.84	2540	2540	2580
5.77	2416	2504	2504
6.23	2540	2613	2540

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.80	3.8	3.8	3.8
2.41	20.1	20.5	22.5
3.01	47.3	47.1	48.0
3.31	48.9	49.4	49.5
3.94	49.3	49.3	49.3
4.53	45.0	45.0	45.0
4.84	41.9	42.0	42.0
5.77	47.0	48.0	48.0
6.23	34.0	35.0	45.8

*D.F.I. is the distance from the ignitor to each of the listed transducer locations

Table 7
Wave Velocities & Pressures For
$\frac{1}{2}\ O_2 + H_2 + He$ At
.5 Atm. Initial Pressure
And 300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run # 3
1.49	373	373	379
3.01	715	827	822
3.31	687	746	754
3.94	804	823	852
4.84	715	738	738
5.77	3329	3670	3550
6.23	2565	2390	2237

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	.91	.91	.91
3.01	.81	.85	.79
3.31	.99	.99	1.00
3.94	.89	.91	.64
4.84	.73	.76	.74
5.77	10.84	3.14	8.80
6.23	3.99	3.99	3.99

*D.F.I. is the distance from the ignitor to each of the listed transducer positions

Table 8
Wave Velocities And Pressures For
$\frac{1}{2} O_2 + H_2 + He$ At
1 Atm. Initial Pressure And
300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run #3
.90	762	767	784
1.49	560	582	577
3.01	2692	2500	1313
3.31	4868	4801	4963
3.40	4311	4501	4402
4.53	4014	4038	4224
4.84	3895	3939	3895
5.77	3702	3734	3734
6.23	3533	3533	3533

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
.90	4.13	4.55	4.25
1.49	5.33	5.27	4.85
3.01	10.86	15.53	10.85
3.31	103.29	97.12	93.43
3.94	71.25	83.57	78.36
4.53	56.46	57.69	61.39
4.84	52.14	50.29	57.76
5.77	35.27	35.87	35.87
6.23	36.09	34.52	31.38

* D.F.I. is the distance from the ignitor to each of the listed transducer positions

Table 9
Wave Velocities And Pressures For
$\frac{1}{2} O_2 + H_2 + He$ At
2 Atm. Initial Pressure And
300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run #3
.90	746	756	730
1.49	572	567	567
3.01	4429	4290	4429
3.31	4381	3938	4028
3.94	3889	3921	3889
4.53	3671	3710	3671
4.84	3820	3811	3811
5.77	3670	3702	3767
6.23	3505	3505	1326

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
.90	7.53	7.05	7.53
1.49	8.73	8.49	9.45
3.01	30.25	30.25	30.25
3.31	83.34	79.64	78.41
3.94	82.10	83.34	88.27
4.53	64.85	68.55	68.55
4.84	59.92	61.15	61.15
5.77	53.14	50.06	53.76
6.23	75.94	75.94	77.15

*D.F.I. is the distance from the ignitor to each of the listed transducer positions

Table 10

Wave Velocities And Pressures For

$\frac{1}{2} O_2 + H_2 + Ar$ At

.5 Atm. Initial Pressure

And 300 K initial Temperature

Wave Velocities, w_1 (m/s)

D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	331	339	339
3.01	1295	1373	1226
3.31	2645	2695	2695
3.94	2602	2602	2511
4.53	2452	2408	2388
4.84	2369	2369	2369
5.77	2385	2385	2105
6.23	2146	2191	2191

Wave Pressures, p_3 (Atm.)

D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	1.88	2.12	1.99
3.01	4.47	5.43	5.13
3.31	20.94	21.42	22.14
3.94	11.32	11.32	11.44
4.53	9.52	10.84	10.59
4.84	11.44	11.92	8.31
5.77	6.45	6.33	6.27
6.23	5.91	6.15	11.68

*D.F.I. is the distance from the ignitor to each of the listed transducer positions

Table 11

Wave Velocities And Pressures For

$\frac{1}{2}\ O_2 + H_2 + Ar$ At

1 Atm. Initial Pressure And

300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	312	298	319
1.80	960	1131	1002
2.41	2674	2508	2362
3.01	2347	2408	2367
3.31	2336	2336	2336
3.94	2272	2272	2236
4.53	2179	2197	2179
4.84	2262	2262	2262
5.77	2236	2147	2147
6.23	2146	2191	2168

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	5.09	4.61	5.09
1.80	17.59	20.96	21.19
2.41	22.64	23.12	22.16
3.01	23.12	21.92	22.88
3.31	19.76	22.64	21.68
3.94	24.33	23.36	23.12
4.53	19.27	19.27	19.03
4.84	26.25	28.65	31.06
5.77	12.24	12.24	12.24
6.23	22.88	23.12	22.64

* D.F.I. is the distance from the ignitor to each of the listed transducer positions

Table 12

Wave Velocities And Pressures For

$\frac{1}{2} O_2 + H_2 + Ar$ At

2 Atm. Initial Pressure And

300 K Initial Temperature

Wave Velocities, w_1 (m/s)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	1525	2145	2640
1.80	2418	2697	2460
2.41	2508	2362	2486
3.01	2232	2232	2232
3.31	2337	2225	2290
3.94	2236	2236	2202
4.53	2251	2179	2214
4.84	2276	2276	2337
5.77	2284	2213	2284
6.23	2237	2214	2237

Wave Pressures, p_3 (Atm.)			
D.F.I.* (m)	Run #1	Run #2	Run #3
1.49	23.88	23.88	23.40
1.80	29.05	29.65	22.92
2.41	30.86	32.06	31.46
3.01	30.86	30.86	30.86
3.31	23.40	23.64	23.40
3.94	23.16	24.12	24.12
4.53	30.86	30.86	30.86
4.84	41.08	41.08	40.47
5.77	24.12	24.60	24.60
6.23	24.36	24.12	24.12

* D.F.I. is the distance from the ignitor to each of the listed transducer positions

Table 13

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture

At An Initial Pressure Of .1 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
v_xX =0.5 CO_2					
100	3250.52	4.28	1926.87	1026.53	900.34
200	3168.72	2.10	1897.46	1021.87	875.59
300	3127.24	1.39	1875.65	1021.25	854.40
400	3101.54	1.03	1856.93	1023.44	833.49
500	3082.58	.82	1838.09	1025.80	812.29
v_xX =1.0 CO_2					
100	3447.26	5.26	1919.44	1019.10	900.34
200	3345.06	2.59	1895.58	1015.32	880.26
300	3290.99	1.71	1878.56	1015.63	862.93
400	3256.31	1.28	1864.71	1017.83	846.88
500	3230.33	1.02	1850.52	1019.32	831.20
v_xX =1.88 CO_2					
100	3623.73	6.44	1941.11	1030.44	910.67
200	3508.36	3.20	1926.68	1029.98	896.70
300	3446.79	2.13	1916.61	1032.20	884.41
400	3406.91	1.59	1909.07	1035.94	873.13
500	3376.65	1.27	1900.33	1039.14	861.19

Table 14
Detonation Parameters For A
$\frac{1}{2} O_2 + H_2 + v_x X$ Gas Mixture
At An Initial Pressure Of .5 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		$v_x X = 0.5\ CO_2$			
100	3477.16	22.17	1965.95	1050.01	915.94
200	3393.43	10.92	1939.04	1045.82	893.22
300	3351.47	7.22	1919.23	1046.68	872.55
400	3326.36	5.38	1902.41	1049.43	852.97
500	3307.98	4.28	1885.33	1052.31	833.02
		$v_x X = 1.0\ CO_2$			
100	3720.39	27.12	1952.01	1038.15	913.86
200	3610.15	13.40	1931.34	1035.92	895.43
300	3552.23	8.88	1916.58	1037.29	879.29
400	3515.43	6.64	1904.69	1040.42	864.27
500	3487.76	5.29	1892.21	1043.39	848.81
		$v_x X = 1.88\ CO_2$			
100	3928.67	32.62	1955.74	1039.66	916.08
200	3803.22	16.30	1947.64	1042.70	904.93
300	3736.51	10.88	1941.52	1047.06	894.46
400	3693.66	8.18	1937.13	1052.47	884.66
500	3661.13	6.55	1930.94	1056.97	873.96

Table 15

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture

At An Initial Pressure Of 1 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		$v_xX = 0.5\ CO_2$			
100	3577.75	44.99	1981.66	1059.35	922.30
200	3494.21	22.19	1955.99	1055.65	900.34
300	3452.[illegible]	14.68	1937.18	1056.96	880.22
400	3428.47	10.95	1921.27	1060.11	861.15
500	3410.74	8.72	1905.02	1063.33	841.69
		$v_xX = 1.0\ CO_2$			
100	3844.91	54.85	1964.08	1045.32	918.76
200	3731.79	27.15	1945.08	1043.94	901.14
300	3672.54	18.01	1931.45	1045.86	885.59
400	3635.14	13.48	1920.53	1049.44	871.09
500	3607.02	10.75	1908.87	1052.78	856.09
		$v_xX = 1.88\ CO_2$			
100	4067.93	65.32	1957.55	1041.06	916.49
200	3938.98	32.74	1952.72	1045.98	906.74
300	3870.41	21.89	1948.60	1051.45	897.15
400	3826.57	16.49	1945.79	1057.72	888.08
500	3793.25	13.22	1940.87	1062.90	877.97

Table 16
Detonation Parameters For A
$\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture
At An Initial Pressure Of 2 Atm.

T_1 (K)	T_3 (K)	P_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX =0.5 CO_2			
100	3679.15	91.20	1996.47	1068.22	928.26
200	3596.49	45.02	1972.22	1065.82	906.40
300	3556.37	29.83	1954.44	1066.91	887.53
400	3533.17	22.28	1939.47	1070.47	868.99
500	3516.40	17.74	1924.07	1074.04	850.03
		v_xX =1.0 CO_2			
100	3973.04	110.78	1974.71	1051.67	923.04
200	3857.57	54.94	1957.53	1051.27	906.26
300	3797.27	36.49	1945.10	1053.79	891.31
400	3759.51	27.33	1935.21	1057.88	877.33
500	3731.15	21.82	1924.44	1061.63	862.82
		v_xX =1.88 CO_2			
100	4211.32	130.49	1956.20	1040.20	915.99
200	4079.55	65.63	1954.91	1047.05	907.86
300	4009.44	43.95	1952.95	1054.30	898.65
400	3964.91	33.15	1951.87	1061.53	890.34
500	3931.03	26.61	1948.33	1067.47	880.86

Table 17
Detonation Parameters For A
$\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture
At An Initial Pressure Of 5 Atm.

T_1 (K)	T_3 (K)	P_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX =0.5 CO_2			
100	3813.00	231.76	2014.50	1079.07	935.43
200	3733.38	114.63	1992.25	1077.69	914.56
300	3695.45	76.01	1975.94	1080.03	895.91
400	3674.75	56.87	1962.31	1083.60	878.71
500	3659.86	45.34	1948.11	1087.67	860.44
		v_xX =1.0 CO_2			
100	4146.72	279.94	1986.32	1058.61	927.71
200	4029.43	139.15	1971.71	1059.67	912.04
300	3968.48	92.57	1961.02	1063.11	897.90
400	3930.67	69.43	1952.55	1067.92	884.64
500	3902.32	55.49	1942.99	1072.25	870.75
		v_xX =1.88 CO_2			
100	4405.83	323.86	1948.85	1036.14	912.71
200	4271.31	163.63	1952.78	1046.46	906.32
300	4200.15	109.97	1953.96	1054.94	899.02
400	4155.29	83.14	1955.29	1063.54	891.75
500	4121.12	66.86	1953.69	1070.54	883.15

Table 18

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_X X$ Gas Mixture

At An Initial Pressure Of .1 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		$v_X X = 0.5\ N_2$			
100	3245.42	5.15	2372.69	1268.24	1104.45
200	3162.42	2.51	2332.18	1256.58	1075.60
300	3119.27	1.65	2302.52	1251.87	1050.64
400	3091.67	1.23	2276.83	1249.93	1026.90
500	3071.62	.97	2251.55	1249.20	1002.35
		$v_X X = 1.0\ N_2$			
100	3076.23	4.92	2167.68	1162.83	1004.85
200	3015.84	2.41	2134.08	1154.05	980.04
300	2986.41	1.59	2109.01	1150.98	958.03
400	2968.67	1.18	2085.90	1150.08	935.82
500	2957.45	.94	2066.37	1150.41	915.96
		$v_X X = 1.88\ N_2$			
100	2795.14	4.52	1957.86	1060.97	896.89
200	2773.93	2.24	1934.51	1056.45	878.06
300	2769.40	1.48	1916.28	1055.92	860.36
400	2771.53	1.11	1901.40	1057.12	844.28
500	2774.37	.88	1883.28	1058.63	824.66

Table 19

Detonation Parameters For A

$\frac{1}{2}$ O_2 + H_2 + $v_x X$ Gas Mixture

At An Initial Pressure Of .5 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		$v_x X$ =0.5 N_2			
100	3474.69	27.00	2436.16	1306.47	1129.69
200	3389.77	13.22	2397.16	1295.29	1101.88
300	3346.19	8.70	2368.90	1290.98	1077.92
400	3318.84	6.46	2344.72	1289.41	1055.31
500	3299.53	5.12	2322.09	1289.11	1032.98
		$v_x X$ =1.0 N_2			
100	3255.42	25.62	2217.33	1194.30	1023.03
200	3199.67	12.60	2186.35	1186.47	999.88
300	3173.98	8.32	2163.55	1184.12	979.43
400	3159.81	6.19	2143.49	1183.89	959.59
500	3151.07	4.92	2124.40	1184.64	939.76
		$v_x X$ =1.88 N_2			
100	2900.44	23.14	1988.99	1083.68	905.31
200	2891.71	11.52	1970.16	1080.97	889.19
300	2896.35	7.66	1955.26	1081.67	873.59
400	2905.61	5.74	1941.88	1083.73	858.14
500	2915.64	4.58	1927.74	1086.23	841.52

Table 20

Detonation Parameters For A $\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture At An Initial Pressure Of 1 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX =0.5 N_2			
100	3575.95	55.07	2462.75	1322.70	1140.05
200	3491.41	26.98	2424.77	1311.91	1112.87
300	3448.44	17.77	2397.40	1307.90	1089.50
400	3421.76	13.20	2373.99	1306.58	1067.40
500	3403.12	10.47	2352.16	1306.51	1045.65
		v_xX =1.0 N_2			
100	3331.24	52.05	2237.70	1207.41	1030.29
200	3278.86	25.65	2208.26	1200.17	1008.09
300	3255.53	16.95	2186.39	1198.20	988.19
400	3243.37	12.62	2167.14	1198.29	968.85
500	3236.50	10.04	2149.13	1199.35	949.78
		v_xX =1.88 N_2			
100	2940.94	46.70	2000.83	1092.63	908.20
200	2938.37	23.28	1983.99	1090.85	893.15
300	2947.60	15.51	1970.54	1092.20	878.34
400	2960.70	11.63	1958.24	1094.76	863.48
500	2974.27	9.30	1945.54	1097.72	847.83

Table 21

Detonation Parameters For A

$\frac{1}{2}$ O_2 + H_2 + $v_x X$ Gas Mixture

At An Initial Pressure Of 2 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		$v_x X$ =0.5 N_2			
100	3677.82	112.24	2488.72	1338.65	1150.07
200	3594.56	55.06	2452.07	1328.38	1123.68
300	3552.71	36.29	2425.69	1324.73	1100.96
400	3527.11	26.98	2403.26	1323.72	1079.53
500	3509.47	21.42	2382.29	1323.92	1058.37
		$v_x X$ =1.0 N_2			
100	3405.30	105.68	2257.23	1220.11	1037.12
200	3357.10	52.15	2229.32	1213.56	1015.75
300	3336.76	34.49	2208.65	1212.06	996.60
400	3327.15	25.72	2190.53	1212.54	977.9[illegible]
500	3322.42	20.47	2173.33	1213.92	959.40
		$v_x X$ =1.88 N_2			
100	2978.03	94.14	2011.59	1100.95	910.64
200	2981.84	47.02	1996.68	1100.18	896.50
300	2996.01	31.37	1984.75	1102.24	882.52
400	3013.39	23.55	1973.75	1105.37	868.38
500	3030.87	18.85	1962.48	1108.86	853.62

Table 22

Detonation Parameters For A

$\frac{1}{2}$ O_2 + H_2 + v_xX Gas Mixture

At An Initial Pressure Of 5 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX =0.5 N_2			
100	3811.65	287.29	2521.66	1359.01	1162.65
200	3731.96	141.20	2487.16	1349.71	1137.46
300	3692.57	93.17	2462.29	1346.66	1115.62
400	3669.12	69.34	2441.12	1346.15	1094.97
500	3653.40	55.11	2421.37	1346.77	1074.60
		v_xX =1.0 N_2			
100	3499.02	269.04	2281.36	1236.06	1045.30
200	3457.83	133.[illegible]4	2255.86	1230.62	1025.23
300	3442.43	88.14	2236.92	1229.86	1007.07
400	3436.98	65.81	2220.38	1230.96	989.42
500	3435.83	52.44	2204.57	1232.85	971.72
		v_xX =1.88 N_2			
100	3021.78	237.48	2024.24	1110.96	913.28
200	3034.29	118.88	2011.87	1111.62	900.25
300	3055.41	79.47	2002.03	1114.71	887.32
400	3078.73	59.76	1992.77	1118.68	874.10
500	3101.56	47.91	1983.17	1122.88	860.30

Table 23

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_x X$ Gas Mixture

At An Initial Pressure Of .1 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		$v_x X$ =0.5 He			
100	3340.04	5.41	3081.84	1651.80	1430.05
200	3242.17	2.63	3023.08	1632.31	1390.77
300	3190.51	1.72	2981.16	1623.53	1357.63
400	3156.90	1.28	2945.63	1618.99	1326.64
500	3132.39	1.01	2912.73	1616.46	1296.27
		$v_x X$ =1.0 He			
100	3253.20	5.35	3277.05	1764.49	1512.56
200	3165.57	2.61	3215.48	1743.50	1471.98
300	3120.12	1.71	3171.56	1734.03	1437.54
400	3091.03	1.27	3134.12	1729.06	1405.06
500	3070.13	1.00	3099.15	1726.28	1372.88
		$v_x X$ =1.88 He			
100	3119.40	5.20	3503.59	1902.35	1601.23
200	3048.82	2.54	3441.49	1880.38	1561.10
300	3013.76	1.67	3396.63	1870.58	1526.04
400	2989.83	1.24	3355.71	1864.43	1491.28
500	2975.45	.98	3320.11	1861.81	1458.31

Table 24

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture

At An Initial Pressure Of .5 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX =0.5 He			
100	3606.49	28.58	3178.81	1710.94	1467.87
200	3501.34	13.93	3121.14	1691.17	1429.97
300	3446.26	9.14	3080.61	1682.39	1398.23
400	3410.67	6.77	3046.53	1677.93	1368.60
500	3384.96	5.36	3015.31	1675.57	1339.74
		v_xX =1.0 He			
100	3497.04	28.24	3378.96	1828.77	1550.19
200	3405.21	13.79	3319.04	1807.49	1511.55
300	3358.07	9.05	3276.75	1798.00	1478.75
400	3328.37	6.71	3241.17	1793.18	1447.99
500	3307.35	5.32	3208.35	1790.60	1417.74
		v_xX = 1.88 He			
100	3327.14	27.28	3605.82	1971.21	1634.60
200	3257.50	13.37	3546.88	1949.29	1597.59
300	3223.94	8.81	3504.83	1939.74	1565.09
400	3204.31	6.55	3469.04	1935.06	1533.98
500	3191.46	5.19	3435.88	1932.76	1503.12

Table 25

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture

At An Initial Pressure Of 1 Atm.

T_1 (K)	T_3 (K)	P_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX = 0.5 He			
100	3727.90	58.53	3220.75	1736.82	1483.93
200	3620.39	28.55	3163.93	1717.15	1446.78
300	3564.25	18.75	3124.19	1708.48	1415.71
400	3528.19	13.90	3090.92	1704.17	1386.76
500	3502.23	11.01	3060.49	1701.94	1358.55
		v_xX =1.0 He			
100	3606.61	57.78	3422.84	1856.93	1565.91
200	3514.01	28.23	3364.06	1835.78	1528.29
300	3466.81	18.56	3322.82	1826.45	1496.37
400	3437.32	13.77	3288.20	1821.80	1466.40
500	3416.65	10.91	3256.43	1819.42	1437.02
		v_xX =1.88 He			
100	3418.07	55.65	3649.19	2001.24	1647.95
200	3350.14	27.32	3592.12	1979.67	1612.45
300	3318.01	18.01	3551.57	1970.40	1581.17
400	3299.73	13.40	3517.17	1965.99	1551.18
500	3288.13	10.64	3485.34	1963.96	1521.37

Table 26

Detonation Parameters For A

$\frac{1}{2}$ O_2 + H_2 + v_xX Gas Mixture

At An Initial Pressure Of 2 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX =0.5 He			
100	3852.48	119.79	3262.36	1762.67	1499.69
200	3743.46	58.49	3206.75	1743.33	1463.42
300	3686.71	38.43	3167.97	1734.89	1433.08
400	3650.48	28.51	3135.65	1730.79	1404.85
500	3624.52	22.60	3106.09	1728.76	1377.33
		v_xX =1.0 He			
100	3718.13	118.12	3466.36	1885.15	1581.21
200	3625.57	57.78	3409.03	1864.33	1544.70
300	3578.76	38.01	3368.95	1855.25	1513.70
400	3549.86	28.23	3335.46	1850.86	1484.60
500	3529.81	22.39	3304.78	1848.71	1456.06
		v_xX=1.88 He			
100	3508.73	113.42	3691.65	2031.17	1660.49
200	3443.61	55.77	3636.90	2010.22	1626.68
300	3413.60	36.81	3598.13	2001.40	1596.73
400	3397.19	27.40	3565.33	1997.39	1567.94
500	3387.23	21.78	3534.99	1995.72	1539.28

Table 27

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_x X$ Gas Mixture

At An Initial Pressure Of 5 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		$v_x X$ = 0.5 He			
100	4020.71	308.38	3316.41	1796.50	1519.92
200	3911.25	150.81	3262.88	1777.91	1484.97
300	3854.59	99.20	3225.66	1769.96	1455.70
400	3818.75	73.67	3194.75	1766.28	1428.47
500	3793.33	58.44	3166.56	1764.63	1401.92
		$v_x X$ = 1.0 He			
100	3866.85	303.61	3522.64	1922.12	1600.51
200	3776.10	148.78	3467.82	1902.13	1565.70
300	3730.89	98.00	3429.70	1893.64	1536.06
400	3703.49	72.86	3397.92	1889.73	1508.19
500	3684.85	57.84	3368.86	1888.03	1480.83
		$v_x X$ = 1.88 He			
100	3626.79	290.23	3745.87	2070.20	1675.67
200	3567.01	143.03	3694.73	2050.49	1644.24
300	3540.93	94.57	3658.70	2042.54	1616.17
400	3527.84	70.50	3628.31	2039.25	1589.06
500	3520.77	56.11	3600.17	2038.20	1561.96

Table 28

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_x X$ Gas Mixture

At An Initial Pressure Of .1 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
			$v_x X$ =0.5 Ar		
100	3340.04	5.41	2237.11	1199.04	1038.07
200	3242.16	2.63	2194.44	1184.89	1009.55
300	3190.52	1.72	2164.04	1178.52	985.52
400	3156.89	1.28	2138.15	1175.21	962.94
500	3132.39	1.01	2114.35	1173.38	940.96
			$v_x X$ =1.0 Ar		
100	3253.20	5.35	2019.80	1087.54	932.26
200	3165.59	2.61	1981.90	1074.61	907.30
300	3120.09	1.71	1954.70	1068.76	885.95
400	3090.99	1.27	1931.61	1065.70	865.91
500	3070.14	1.00	1910.19	1063.99	846.20
			$v_x X$ =1.88 Ar		
100	3119.41	5.20	1834.98	996.33	838.64
200	3048.82	2.54	1802.44	984.83	817.61
300	3013.79	1.67	1779.02	979.70	799.31
400	2989.82	1.24	1757.50	976.47	781.03
500	2975.43	.98	1738.81	975.09	763.72

Table 29

Detonation Parameters For A

$\frac{1}{2} O_2 + H_2 + v_x X$ Gas Mixture

At An Initial Pressure Of .5 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		$v_x X$ =0.5 Ar			
100	3606.48	28.58	2307.48	1241.97	1065.52
200	3501.34	13.93	2265.62	1227.61	1038.00
300	3446.25	9.14	2236.20	1221.24	1014.96
400	3410.67	6.77	2211.47	1218.01	993.46
500	3384.95	5.36	2188.80	1216.29	972.51
		$v_x X$ =1.0 Ar			
100	3497.05	28.24	2082.62	1127.16	955.46
200	3405.21	13.79	2045.70	1114.04	931.65
300	3358.08	9.05	2019.64	1108.20	911.44
400	3328.36	6.71	1997.66	1105.22	892.44
500	3307.36	5.32	1977.48	1103.64	873.84
		$v_x X$ =1.88 Ar			
100	3327.14	27.28	1888.50	1032.40	856.10
200	3257.49	13.37	1857.62	1020.92	836.71
300	3223.94	8.81	1835.61	1015.92	819.69
400	3204.30	6.55	1816.85	1013.46	803.39
500	3191.46	5.19	1799.49	1012.26	787.23

Table 30
Detonation Parameters For A
$\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture
At An Initial Pressure Of 1 Atm.

T_1 (K)	T_3 (K)	P_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX =0.5 Ar			
100	3727.90	58.53	2337.93	1260.75	1077.18
200	3620.39	28.55	2296.69	1246.48	1050.21
300	3564.24	18.75	2267.84	1240.18	1027.66
400	3528.19	13.90	2243.70	1237.05	1006.65
500	3502.22	11.01	2221.60	1235.43	986.17
		v_xX =1.0 Ar			
100	3606.61	57.78	2109.66	1144.51	965.15
200	3514.01	28.23	2073.44	1131.48	941.96
300	3466.80	18.56	2048.01	1125.73	922.28
400	3437.32	13.77	2026.66	1122.86	903.80
500	3416.64	10.91	2007.09	1121.39	885.70
		v_xX =1.88 Ar			
100	3418.07	55.65	1911.22	1048.12	863.09
200	3350.14	27.32	1881.33	1036.82	844.50
300	3318.02	18.01	1860.10	1031.97	828.13
400	3299.74	13.40	1842.08	1029.66	812.42
500	3288.14	10.64	1825.41	1028.60	796.81

Table 31

Detonation Parameters For A

$\frac{1}{2}\ O_2 + H_2 + v_xX$ Gas Mixture

At An Initial Pressure Of 2 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
		v_xX =0.5 Ar			
100	3852.48	119.79	2368.14	1279.52	1088.63
200	3743.45	58.49	2327.77	1265.48	1062.29
300	3686.71	38.43	2299.63	1259.35	1040.27
400	3650.48	28.51	2276.16	1256.38	1019.78
500	3624.52	22.60	2254.71	1254.91	999.80
		v_xX =1.0 Ar			
100	3718.13	118.12	2136.48	1161.91	974.57
200	3625.57	57.78	2101.15	1149.07	952.07
300	3578.75	38.01	2076.44	1143.48	932.96
400	3549.86	28.23	2055.80	1140.77	915.02
500	3529.81	22.39	2036.89	1139.45	897.44
		v_xX =1.88 Ar			
100	3508.72	113.42	1933.45	1063.80	869.66
200	3443.60	55.77	1904.78	1052.83	851.95
300	3413.60	36.81	1884.48	1048.21	836.27
400	3397.19	27.40	1867.30	1046.11	821.19
500	3387.22	21.78	1851.40	1045.23	806.17

Table 32

Detonation Parameters For A

$\frac{1}{2}$ O_2 + H_2 + v_xX Gas Mixture

At An Initial Pressure Of 5 Atm.

T_1 (K)	T_3 (K)	p_3 (Atm.)	w_1 (m/s)	w_3 (m/s)	u_3 (m/s)
v_xX =0.5 Ar					
100	4020.71	308.38	2407.37	1304.07	1103.30
200	3911.25	150.81	2368.52	1290.58	1077.94
300	3854.59	99.20	2341.50	1284.81	1056.69
400	3818.75	73.67	2319.06	1282.14	1036.92
500	3793.33	58.44	2298.60	1280.94	1017.66
v_xX =1.0 Ar					
100	3866.85	303.61	2171.17	1184.70	986.47
200	3776.10	148.78	2137.38	1172.37	965.01
300	3730.89	98.01	2113.89	1167.14	946.74
400	3703.49	72.86	2094.30	1164.73	929.57
500	3684.85	57.84	2076.39	1163.68	912.71
v_xX =1.88 Ar					
100	3626.79	290.23	1961.85	1084.24	877.61
200	3567.01	143.03	1935.07	1073.92	861.15
300	3540.93	94.57	1916.20	1069.75	846.45
400	3527.84	70.50	1900.28	1068.03	832.25
500	3520.77	56.11	1885.54	1067.48	818.06

Table 33

Diffuser Efficiency, η_D, And Entropy Increment, $\frac{\Delta s}{R}$, For N.S. At Inlet

M_F (M_∞)	p^o_∞ (Atm.)	p^o_{DE} (Atm.)	T^o_∞ (K)	T^o_{DE} (K)	$\frac{\Delta S}{R}$	η_D
1	.0201	.0201	279.64	279.64	.0000	1.0000
2	.0825	.0603	418.41	418.41	.0109	.6911
3	.3910	.1291	643.58	643.58	.0384	.3113
4	1.6717	.2260	941.65	941.65	.0694	.1297
5	6.2368	.3510	1302.0	1302.0	.0997	.0547
6	20.590	.5052	1718.2	1718.0	.1285	.0240
7	61.330	.6881	2180.7	2173.6	.1557	.0111
8	168.14	.9009	2678.9	2615.6	.1817	.0053
9	431.72	1.1448	3207.4	2986.9	.2075	.0026
10	1047.3	1.4193	3766.5	3301.7	.2339	.0013

$T_\infty = 233.1$ K $\quad p_\infty = .01068$ Atm. $\quad (s/R)^{T_\infty}_{eq\ air} = .95597$ kmol/kg

Altitude = 100000 feet

Table 34
Detonation Induction Distances
For A $\frac{1}{2}O_2 + H_2 + v_xX$ Gas
At Initial Pressure Of p_1 atm.

p_1 = 0.5 atm.	
$v_xX = \frac{1}{2}\ CO_2$	475 cm
$v_xX = N_2$	475 cm
$v_xX = He$	575 cm
$v_xX = Ar$	320 cm
p_1 = 1.0 atm.	
$v_xX = \frac{1}{2}\ CO_2$	375 cm
$v_xX = N_2$	325 cm
$v_xX = He$	325 cm
$v_xX = Ar$	225 cm
p_1 = 2.0 atm.	
$v_xX = \frac{1}{2}\ CO_2$	350 cm
$v_xX = N_2$	310 cm
$v_xX = He$	280 cm
$v_xX = Ar$	175 cm

Table 35
Absolute Formation Enthalpies

For Eleven Species

At 0 Degrees Kelvin

Species	$\left(\frac{H_f^o}{\mathcal{R}}\right)_i$ (K)
CO	-13688
CO_2	-47286
H	25982
H_2	0
H_2O	-28736
N	56613
N_2	0
NO	10799
O	29685
O_2	0
OH	4675

Table 36
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.7	T	233.10	278.48	2053.48	2012.70
		P	.01068	.01982	.01264	.01068
		u	306.598	48.285	613.852	762.174
2	.7	T	233.10	415.92	2143.02	1695.06
		P	.01068	.08069	.05218	.01068
		u	613.197	71.527	626.528	1478.681
3	.7	T	233.10	638.06	2271.83	1312.58
		P	.01068	.37867	.25007	.01068
		u	919.795	108.709	644.899	1937.697
4	.7	T	233.10	930.81	2434.11	1038.53
		P	.01068	1.5969	1.0821	.01068
		u	1226.39	156.949	668.015	2259.21
5	.7	T	233.10	1283.11	2627.90	854.41
		P	.01068	5.8679	4.0904	.01068
		u	1532.99	213.804	695.358	2523.51
6	.7	T	233.10	1688.02	2851.89	729.978
		P	.01068	19.034	13.655	.01068
		u	1839.59	277.480	726.530	2765.06
7	.7	T	233.10	2136.89	3106.21	644.356
		P	.01068	55.704	41.002	.01068
		u	2146.19	345.655	761.307	2999.80
8	.7	T	233.10	2619.88	3392.33	584.986
		P	.01068	150.13	112.41	.01068
		u	2452.79	415.573	799.604	3234.66
9	.7	T	233.10	3131.56	3712.68	543.776
		P	.01068	379.54	284.06	.01068
		u	2759.38	485.401	841.440	3472.72
10	.7	T	233.10	3671.80	4069.18	517.993
		P	.01068	908.10	657.68	.01068
		u	3065.98	554.606	886.736	3714.45

i-inlet DE- diffuser exit c- combustion chamber exit
e- nozzle exit

Propane Fuel at T_f = 230.9 K ---- Isentropic Diffuser

Table 37
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.7	T	233.10	278.48	2053.48	2012.70
		P	.01068	.01982	.01264	.01068
		u	306.598	48.285	613.852	762.174
2	.7	T	392.70	415.91	2132.84	1787.86
		P	.04809	.05899	.03815	.01068
		u	229.388	71.683	625.406	1364.62
3	.7	T	617.77	637.97	2231.75	1650.84
		P	.11082	.12492	.08254	.01068
		u	234.890	109.622	640.656	1664.92
4	.7	T	912.59	930.42	2348.70	1606.90
		P	.19971	.21558	.14640	.01068
		u	256.719	159.702	659.369	1878.18
5	.7	T	1268.95	1281.95	2479.27	1629.06
		P	.31539	.32904	.23069	.01068
		u	282.548	220.226	681.063	2062.50
6	.7	T	1680.62	1685.01	2619.06	1699.35
		P	.45823	.46355	.33684	.01068
		u	309.078	290.364	705.339	2235.79
7	.7	T	2134.10	2125.47	2765.03	1803.88
		P	.62901	.61673	.46565	.01068
		u	333.733	368.120	732.017	2403.52
8	.7	T	2580.15	2558.19	2915.42	1925.30
		P	.83015	.78865	.61725	.01068
		u	351.001	445.601	761.071	2567.53
9	.7	T	2957.69	2926.68	3069.59	2729.09
		P	1.0639	.98434	.79172	.01068
		u	358.307	512.685	792.661	2729.09
10	.7	T	3275.66	3236.65	3227.64	2154.09
		P	1.3287	1.2028	.98642	.01068
		u	361.549	570.773	826.944	2898.31

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

Propane Fuel at T_f = 230.9 K ---- Normal Shock Diffuser

Tables 38

Temperature, Pressure and Velocity

At Four Ramjet Stations

M_F	M_c		i	DE	c	c
1	.8	T	233.10	278.41	2031.24	2016.88
		P	.01068	.01980	.01133	.01068
		u	306.598	49.793	697.344	746.722
2	.8	T	233.10	415.76	2118.95	1698.95
		P	.01068	.08058	.04680	.01068
		u	613.197	73.838	711.621	1474.29
3	.8	T	233.10	637.68	2245.84	1317.89
		P	.01068	.37783	.22442	.01068
		u	919.795	112.387	732.409	1933.94
4	.8	T	233.10	930.02	2406.18	1042.75
		P	.01068	1.5916	.97209	.01068
		u	1226.39	162.558	758.605	2256.78
5	.8	T	233.10	1281.64	2598.06	857.85
		P	.01068	5.8400	3.6784	.01068
		u	1532.99	221.924	789.647	2521.81
6	.8	T	233.10	1685.52	2819.70	732.81
		P	.01068	18.909	12.292	.01068
		u	1839.59	288.754	825.015	2763.82
7	.8	T	233.10	2132.96	3071.05	646.80
		P	.01068	55.222	36.945	.01068
		u	2146.19	360.747	864.421	2998.83
8	.8	T	233.10	2614.17	3353.36	587.26
		P	.01068	148.48	101.35	.01068
		u	2452.79	435.095	907.774	3233.85
9	.8	T	233.10	3123.67	3668.86	545.88
		P	.01068	374.45	256.12	.01068
		u	2759.38	509.870	955.070	3472.02
10	.8	T	233.10	3661.31	4019.16	520.14
		P	.01068	893.70	592.30	.01068
		u	3065.98	584.492	1006.20	3713.79

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

Propane Fuel at T_f = 230.9 K ---- Isentropic Diffuser

Table 39
Temperature, Pressure and Velocity
Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.8	T	233.10	278.41	2031.24	2016.88
		P	.01068	.01980	.01133	.01068
		u	306.598	49.793	697.343	746.722
2	.8	T	392.70	415.75	2109.34	1791.40
		P	.04809	.05891	.03421	.01068
		u	229.388	73.991	710.404	1359.78
3	.8	T	617.77	637.58	2207.86	1656.50
		P	.11082	.12464	.07407	.01068
		u	234.890	113.287	727.788	1659.49
4	.8	T	912.59	929.62	2324.79	1612.37
		P	.19971	.21485	.13149	.01068
		u	256.719	165.303	749.156	1873.69
5	.8	T	1268.95	1280.43	2455.36	1634.11
		P	.31539	.32742	.20743	.01068
		u	282.548	228.418	773.909	2058.67
6	.8	T	1680.62	1682.32	2594.94	1703.95
		P	.45823	.46029	.30321	.01068
		u	309.078	301.967	801.548	2232.36
7	.8	T	2134.10	2121.15	2740.37	1807.83
		P	.62901	.61067	.41963	.01068
		u	333.733	384.145	831.869	2400.40
8	.8	T	2580.15	2552.48	2889.89	1928.39
		P	.83015	.77840	.55690	.01068
		u	351.001	466.901	864.835	2564.72
9	.8	T	2957.69	2920.19	3042.73	2049.56
		P	1.0639	.96847	.71480	.01068
		u	358.307	539.227	900.603	2726.48
10	.8	T	3275.66	3229.28	3199.02	2155.65
		P	1.3287	1.1802	.89094	.01068
		u	361.549	602.108	939.369	2896.25

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

Propane Fuel at T_f = 230.9 K ---- Normal Shock Diffuser

Table 40
Temperature,Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.9	T	233.10	278.38	2006.44	2019.16
		P	.01068	.01979	.01014	.01068
		u	306.598	50.461	779.233	738.083
2	.9	T	233.10	415.68	2092.17	1701.01
		P	.01068	.08052	.04187	.01068
		u	613.197	74.876	795.042	1471.97
3	.9	T	233.10	637.50	2217.00	1320.94
		P	.01068	.37744	.20088	.01068
		u	919.795	114.057	818.173	1931.78
4	.9	T	233.10	929.65	2375.40	1045.24
		P	.01068	1.5891	.87052	.01068
		u	1226.39	165.123	847.413	2255.35
5	.9	T	233.10	1280.95	2565.24	859.93
		P	.01068	5.8269	3.2959	.01068
		u	1532.99	225.658	882.086	2520.78
6	.9	T	233.10	1684.33	2784.42	734.51
		P	.01068	18.8505	11.0194	.01068
		u	1839.59	293.974	921.557	2763.08
7	.9	T	233.10	2131.06	3032.63	648.28
		P	.01068	54.9910	33.1350	.01068
		u	2146.19	367.805	965.479	2998.24
8	.9	T	233.10	2611.37	3310.94	588.66
		P	.01068	147.68	90.932	.01068
		u	2452.79	444.344	1013.75	3233.35
9	.9	T	233.10	3119.73	3621.36	547.18
		P	.01068	371.93	229.79	.01068
		u	2759.38	521.645	1066.34	3471.59
10	.9	T	233.10	3655.96	3965.27	521.48
		P	.01068	886.44	531.13	.01068
		u	3065.98	599.137	1123.12	3713.37

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

<u>Propane Fuel at</u> T_f = 230.9 K ---- <u>Isentropic Diffuser</u>

Table 41
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.9	T	233.10	278.38	2006.44	2019.16
		P	.01068	.01979	.01014	.01068
		u	306.598	50.461	779.233	738.083
2	.9	T	392.70	415.67	2083.24	1793.82
		P	.04809	.05887	.03061	.01068
		u	229.387	75.021	793.765	1356.450
3	.9	T	617.77	637.41	2181.45	1666.66
		P	.11082	.12452	.06630	.01068
		u	234.890	114.916	813.288	1649.62
4	.9	T	912.59	929.26	2298.43	1615.44
		P	.19971	.21452	.11774	.01068
		u	256.719	167.775	837.306	1871.17
5	.9	T	1268.95	1279.74	2429.15	1636.90
		P	.31539	.32669	.18581	.01068
		u	282.548	232.000	865.121	2056.54
6	.9	T	1680.62	1681.11	2568.66	1706.59
		P	.45823	.45883	.27173	.01068
		u	309.078	307.007	896.119	2230.39
7	.9	T	2134.10	2119.22	2713.58	1810.05
		P	.62901	.60800	.37622	.01068
		u	333.733	391.095	930.018	2398.63
8	.9	T	2580.15	2549.91	2862.25	1930.11
		P	.83015	.77383	.49948	.01068
		u	351.001	476.154	966.831	2563.13
9	.9	T	2957.69	2917.25	3013.70	2050.91
		P	1.0639	.96136	.64120	.01068
		u	358.307	550.809	1006.66	2724.99
10	.9	T	3275.66	3225.94	3168.18	2156.55
		P	1.3287	1.1702	.79916	.01068
		u	361.549	615.779	1049.78	2895.05

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

Propane Fuel at T_f = 230.9 K ---- Normal Shock Diffuser

Table 42
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.7	T	233.10	278.61	2109.63	2070.47
		P	.01068	.01985	.01262	.01068
		u	306.598	45.632	668.176	821.976
2	.7	T	233.10	416.19	2199.44	1752.95
		P	.01068	.08088	.05207	.01068
		u	613.197	67.576	681.164	1588.08
3	.7	T	233.10	638.65	2325.21	1330.95
		P	.01068	.37997	.24933	.01068
		u	919.795	102.704	699.607	2100.17
4	.7	T	233.10	931.96	2481.09	1036.73
		P	.01068	1.6048	1.0776	.01068
		u	1226.39	148.328	722.511	2437.01
5	.7	T	233.10	1285.11	2666.17	837.10
		P	.01068	5.9061	4.0644	.01068
		u	1532.99	202.162	749.489	2707.69
6	.7	T	233.10	1691.18	2879.39	701.59
		P	.01068	19.1920	13.5020	.01068
		u	1839.59	262.551	780.156	2951.05
7	.7	T	233.10	2141.40	3119.45	608.60
		P	.01068	56.2619	40.0612	.01068
		u	2146.19	327.458	814.180	3184.95
8	.7	T	233.10	2625.72	3384.87	545.59
		P	.01068	151.826	106.755	.01068
		u	2452.79	394.620	851.225	3417.33
9	.7	T	233.10	3138.47	3673.76	507.19
		P	.01068	384.054	253.568	.01068
		u	2759.38	462.860	891.069	3651.03
10	.7	T	233.10	3679.20	3980.50	491.24
		P	.01068	918.372	522.008	.01068
		u	3065.98	532.523	933.227	3886.65

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

Hydrogen Fuel at T_f = 20 K ---- Isentropic Diffuser

Table 43
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.7	T	233.10	278.61	2109.63	2070.46
		P	.01068	.01985	.01262	.01068
		u	306.598	45.632	668.176	822.044
2	.7	T	392.70	416.18	2188.08	1848.14
		P	.04809	.05913	.03807	.01068
		u	229.388	67.732	679.876	1460.53
3	.7	T	617.77	638.57	2281.74	1677.94
		P	.11082	.12536	.08230	.01068
		u	234.890	103.591	694.837	1805.15
4	.7	T	912.59	931.62	2390.65	1615.93
		P	.19971	.21668	.14583	.01068
		u	256.719	150.937	713.008	2029.16
5	.7	T	1268.95	1284.09	2510.55	1619.21
		P	.31539	.33133	.22956	.01068
		u	282.548	208.175	733.908	2219.91
6	.7	T	1680.62	1688.50	2636.61	1670.68
		P	.45823	.46782	.33490	.01068
		u	309.078	274.561	757.091	2398.02
7	.7	T	2134.10	2130.55	2764.99	1759.93
		P	.62901	.62392	.46266	.01068
		u	333.733	348.325	782.260	2569.89
8	.7	T	2580.15	2564.11	2893.49	1875.01
		P	.83015	.79943	.61308	.01068
		u	351.001	422.326	809.331	2737.42
9	.7	T	2957.69	2932.46	3021.42	1999.49
		P	1.0639	.99871	.78678	.01068
		u	358.307	487.737	838.415	2901.27
10	.7	T	3275.66	3242.09	3148.43	2115.75
		P	1.3287	1.2197	.98146	.01068
		u	361.549	546.464	869.610	3065.32

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

<u>Hydrogen Fuel at</u> T_f = 20 K ---- <u>Normal Shock Diffuser</u>

Table 44
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.8	T	233.10	278.54	2087.11	2073.03
		P	.01068	.01983	.01131	.01068
		u	306.598	47.054	759.128	811.479
2	.8	T	233.10	416.04	2174.74	1752.40
		P	.01068	.08078	.04669	.01068
		u	613.197	69.755	773.717	1588.74
3	.8	T	233.10	638.31	2298.12	1336.56
		P	.01068	.37923	.22374	.01068
		u	919.795	106.171	794.500	2095.98
4	.8	T	233.10	931.26	2451.96	1041.17
		P	.01068	1.6001	.96793	.01068
		u	1226.39	153.600	820.461	2434.34
5	.8	T	233.10	1283.82	2635.05	840.70
		P	.01068	5.8814	3.6542	.01068
		u	1532.99	209.767	851.075	2705.84
6	.8	T	233.10	1688.98	2846.09	704.53
		P	.01068	19.0816	12.1499	.01068
		u	1839.59	273.058	885.887	2949.69
7	.8	T	233.10	2137.95	3083.63	611.21
		P	.01068	55.8356	36.0670	.01068
		u	2146.19	341.446	924.478	3183.87
8	.8	T	233.10	2620.72	3346.00	548.10
		P	.01068	150.368	96.074	.01068
		u	2452.79	412.64	966.471	3416.37
9	.8	T	233.10	3131.54	3631.08	509.82
		P	.01068	379.531	227.722	.01068
		u	2759.38	485.444	1011.58	3650.10
10	.8	T	233.10	3669.86	3933.17	494.60
		P	.01068	905.422	466.656	.01068
		u	3065.98	560.261	1059.26	3885.55

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

<u>Hydrogen Fuel at</u> T_f = 20 K ---- <u>Isentropic Diffuser</u>

Table 45
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.8	T	233.10	278.54	2087.11	2073.03
		P	.01068	.01983	.01131	.01068
		u	306.598	47.054	759.128	811.480
2	.8	T	392.70	416.03	2164.06	1847.28
		P	.04809	.05905	.03414	.01068
		u	229.388	69.907	772.324	1461.82
3	.8	T	617.77	638.23	2257.20	1683.89
		P	.11082	.12511	.07385	.01068
		u	234.890	107.039	789.357	1799.16
4	.8	T	912.59	930.91	2366.20	1621.72
		P	.19971	.21603	.13097	.01068
		u	256.719	156.183	810.118	2024.20
5	.8	T	1268.95	1282.75	2486.39	1624.61
		P	.31539	.32990	.20638	.01068
		u	282.548	215.801	833.994	2215.67
6	.8	T	1680.62	1686.15	2612.71	1675.70
		P	.45823	.46495	.30139	.01068
		u	309.078	285.273	860.445	2394.24
7	.8	T	2134.10	2126.82	2741.12	1764.53
		P	.62901	.61863	.41682	.01068
		u	333.733	362.977	889.107	2566.40
8	.8	T	2580.15	2559.23	2869.42	1878.79
		P	.83015	.79052	.55295	.01068
		u	351.001	441.623	919.894	2734.29
9	.8	T	2957.69	2926.90	2996.73	2002.52
		P	1.0639	.98490	.71014	.01068
		u	358.307	511.719	952.880	2898.30
10	.8	T	3275.66	3235.69	3122.89	2117.66
		P	1.3287	1.1999	.88629	.01068
		u	361.549	574.933	988.237	3062.98

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

Hydrogen Fuel at T_f = 20 K ---- Normal Shock Diffuser

Table 46

Temperature, Pressure and Velocity

At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.9	T	233.10	278.51	2062.04	2075.35
		P	.01068	.01982	.01012	.01068
		u	306.598	47.6845	848.371	801.780
2	.9	T	233.10	415.97	2147.23	1749.86
		P	.01068	.08073	.04178	.01068
		u	613.200	70.741	864.458	1591.82
3	.9	T	233.10	638.15	2268.11	1339.77
		P	.01068	.37688	.20027	.01068
		u	919.79	107.764	887.516	2093.57
4	.9	T	233.10	930.93	2419.68	1043.77
		P	.01068	1.5978	.86681	.01068
		u	1226.39	156.049	916.425	2432.77
5	.9	T	233.10	1283.19	2600.67	842.83
		P	.01068	5.8695	3.2743	.01068
		u	1532.99	213.325	950.610	2704.74
6	.9	T	233.10	1687.91	2809.44	706.28
		P	.01068	19.0283	10.8916	.01068
		u	1839.59	278.078	989.496	2948.89
7	.9	T	233.10	2136.26	3044.39	612.76
		P	.01068	55.6278	32.3415	.01068
		u	2146.19	348.085	1032.57	3183.22
8	.9	T	233.10	2618.24	3303.62	549.63
		P	.01068	149.651	86.1394	.01068
		u	2452.79	421.279	1079.41	3415.79
9	.9	T	233.10	3128.07	3584.94	511.35
		P	.01068	377.279	203.981	.01068
		u	2759.38	496.39	1129.66	3649.56
10	.9	T	233.10	3665.10	3882.57	496.49
		P	.01068	898.885	417.116	.01068
		u	3065.98	573.868	1182.73	3884.93

i-inlet DE-diffuser exit c-combustion chamber exit

e-nozzle exit

Hydrogen Fuel at T_f = 20 K ---- Isentropic Diffuser

Table 47
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.9	T	233.10	278.51	2062.04	2075.33
		P	.01068	.01982	.01012	.01068
		u	306.596	47.684	848.371	801.869
2	.9	T	392.70	415.96	2137.30	1844.57
		P	.04809	.05902	.03054	.01068
		u	229.388	70.884	862.991	1465.82
3	.9	T	617.77	638.07	2229.95	1687.23
		P	.11082	.12500	.06609	.01068
		u	234.890	108.588	882.084	1795.76
4	.9	T	912.59	930.59	2339.18	1625.01
		P	.19971	.21573	.11727	.01068
		u	256.719	158.525	905.455	2021.37
5	.9	T	1268.95	1282.14	2459.89	1627.63
		P	.31539	.32925	.18488	.01068
		u	282.548	219.172	932.341	2213.29
6	.9	T	1680.62	1685.10	2586.63	1678.54
		P	.45823	.46366	.27011	.01068
		u	309.078	289.971	962.057	2392.08
7	.9	T	2134.10	2125.14	2715.17	1767.13
		P	.62901	.61626	.37373	.01068
		u	333.733	369.376	994.183	2564.41
8	.9	T	2580.15	2557.03	2843.36	1880.91
		P	.83015	.78655	.49597	.01068
		u	351.001	450.033	1028.64	2732.52
9	.9	T	2957.69	2924.40	2970.12	2004.26
		P	1.0639	.97874	.63709	.01068
		u	358.307	522.157	1065.47	2896.58
10	.9	T	3275.66	3232.81	3095.36	2118.75
		P	1.3287	1.1910	.79516	.01068
		u	361.549	587.312	1104.87	3061.63

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

<u>Hydrogen Fuel at</u> T_f = 20 K ---- <u>Normal Shock Diffuser</u>

Table 48

Temperature, Pressure and Velocity

At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.7	T	233.10	278.55	2150.14	2112.65
		P	.01068	.01983	.01299	.01068
		u	306.598	46.833	675.816	826.230
2	.7	T	233.10	416.07	2243.46	1783.94
		P	.01068	.08080	.05358	.01068
		u	613.197	69.320	689.090	1644.48
3	.7	T	233.10	638.40	2371.71	1376.26
		P	.01068	.37941	.25648	.01068
		u	919.795	105.349	707.639	2138.21
4	.7	T	233.10	931.45	2528.40	1071.60
		P	.01068	1.6013	1.1087	.01068
		u	1226.39	152.219	730.446	2478.04
5	.7	T	233.10	1284.18	2713.07	863.83
		P	.01068	5.8884	4.1878	.01068
		u	1532.99	207.635	757.185	2749.74
6	.7	T	233.10	1689.65	2925.65	721.48
		P	.01068	19.1151	13.9877	.01068
		u	1839.59	269.908	787.604	2993.12
7	.7	T	233.10	2139.08	3165.79	621.86
		P	.01068	55.9754	42.1524	.01068
		u	2146.188	336.914	821.452	3226.91
8	.7	T	233.10	2622.54	3433.97	550.29
		P	.01068	150.898	116.781	.01068
		u	2452.79	406.176	858.541	3459.78
9	.7	T	233.10	3134.45	3732.23	498.00
		P	.01068	381.424	302.656	.01068
		u	2759.38	476.097	898.873	3695.65
10	.7	T	233.10	3674.62	4062.73	457.77
		P	.01068	912.009	740.096	.01068
		u	3065.98	546.288	942.380	3936.45

i-inlet DE-diffuser exit c-combustion chamber exit

e-nozzle exit

Hydrogen Fuel at T_f = 300 K ---- Isentropic Diffuser

Table 49

Temperature, Pressure and Velocity

At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.7	T	233.10	278.55	2150.14	2112.65
		P	.01068	.01983	.01299	.01068
		u	306.598	46.833	675.816	826.231
2	.7	T	392.70	416.06	2230.55	1877.40
		P	.04809	.05907	.03917	.01068
		u	229.388	69.504	687.640	1519.05
3	.7	T	617.77	638.29	2322.84	1727.66
		P	.11082	.12516	.08467	.01068
		u	234.890	106.388	702.352	1838.26
4	.7	T	912.59	931.04	2428.46	1663.52
		P	.19971	.21615	.15001	.01068
		u	256.719	155.238	720.087	2062.52
5	.7	T	1268.95	1282.98	2544.36	1664.07
		P	.31539	.33015	.23615	.01068
		u	282.548	214.500	740.511	2252.53
6	.7	T	1680.62	1686.55	2666.46	1712.75
		P	.45823	.46543	.34454	.01068
		u	309.078	283.516	763.250	2429.12
7	.7	T	2134.10	2127.44	2791.49	1798.18
		P	.62901	.61951	.47606	.01068
		u	333.733	360.568	788.081	2599.29
8	.7	T	2580.15	2560.07	2917.30	1907.76
		P	.83015	.79206	.63100	.01068
		u	351.001	438.344	814.907	2765.07
9	.7	T	2957.69	2927.93	3043.16	2025.63
		P	1.0639	.98743	.80976	.01068
		u	358.307	507.391	843.827	2927.33
10	.7	T	3275.66	3236.95	3168.62	2131.89
		P	1.3287	1.2037	1.0099	.01068
		u	361.549	569.428	874.909	3094.65

i-inlet DE-diffuser exit c-combustion chamber exit e-nozzle exit

<u>Hydrogen Fuel at</u> T_f = 300 K ---- <u>Normal Shock Diffuser</u>

Table 50
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.8	T	233.10	278.48	2128.46	2111.38
		P	.01068	.01981	.01165	.01068
		u	306.598	48.338	767.964	831.910
2	.8	T	233.10	415.91	2219.47	1789.55
		P	.01068	.08069	.04809	.01068
		u	613.197	71.629	782.848	1637.62
3	.8	T	233.10	638.03	2345.28	1381.70
		P	.01068	.37860	.23039	.01068
		u	919.795	109.029	803.764	2134.17
4	.8	T	233.10	930.68	2499.68	1075.96
		P	.01068	1.5961	.99683	.01068
		u	1226.39	157.837	829.559	2475.44
5	.8	T	233.10	1282.76	2682.25	867.32
		P	.01068	5.8612	3.7695	.01068
		u	1532.99	215.769	859.892	2747.96
6	.8	T	233.10	1687.21	2892.52	724.29
		P	.01068	18.9935	12.6047	.01068
		u	1839.59	281.197	894.393	2991.84
7	.8	T	233.10	2135.25	3130.03	624.20
		P	.01068	55.5032	38.0273	.01068
		u	2146.19	352.016	932.781	3225.94
8	.8	T	233.10	2616.95	3395.02	552.27
		P	.01068	149.277	105.472	.01068
		u	2452.79	425.719	974.800	3459.04
9	.8	T	233.10	3126.69	3689.43	499.73
		P	.01068	376.391	273.639	.01068
		u	2759.38	500.645	1020.47	3695.05
10	.8	T	233.10	3664.20	4015.15	459.17
		P	.01068	897.655	669.847	.01068
		u	3065.98	576.402	1069.69	3935.99

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

Hydrogen Fuel at T_f = 300 K --- Isentropic Diffuser

Table 51
Temperature,Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.8	T	233.10	278.48	2128.46	2111.38
		P	.01068	.01982	.01165	.01068
		u	306.598	48.338	767.964	831.905
2	.8	T	392.700	415.90	2207.23	1882.57
		P	.04809	.05898	.03516	.01068
		u	229.388	71.811	781.269	1511.28
3	.8	T	617.77	637.92	2298.90	1733.28
		P	.11082	.12489	.07605	.01068
		u	234.890	110.057	797.999	1832.48
4	.8	T	912.59	930.26	2404.49	1668.87
		P	.19971	.21543	.13486	.01068
		u	256.719	160.847	818.240	2057.86
5	.8	T	1268.95	1281.50	2520.55	1669.14
		P	.31539	.32856	.21252	.01068
		u	282.548	222.706	841.554	2248.48
6	.8	T	1680.62	1683.91	2642.82	1717.36
		P	.45823	.46222	.31042	.01068
		u	309.078	295.133	867.490	2425.58
7	.8	T	2134.10	2123.20	2767.77	1802.27
		P	.62901	.61354	.42942	.01068
		u	333.733	376.625	895.751	2596.08
8	.8	T	2580.15	2554.42	2893.28	1911.05
		P	.83015	.78187	.56990	.01068
		u	351.001	459.766	926.231	2762.23
9	.8	T	2957.69	2921.41	3018.52	2028.14
		P	1.0639	.97142	.73198	.01068
		u	358.307	534.353	959.035	2924.75
10	.8	T	3275.66	3229.36	3143.11	2133.40
		P	1.3287	1.1805	.91350	.01068
		u	361.549	601.776	994.260	3092.74

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

Hydrogen Fuel at T_f = 300 K ---- Normal Shock Diffuser

Table 52
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.9	T	233.10	278.45	2104.37	2109.15
		P	.01068	.01981	.01043	.01068
		u	306.598	48.998	858.447	841.742
2	.9	T	233.10	415.84	2192.84	1812.03
		P	.01068	.08064	.04305	.01068
		u	613.197	72.664	874.844	1609.389
3	.9	T	233.10	637.85	2315.96	1384.89
		P	.01068	.37822	.20631	.01068
		u	919.795	110.708	898.013	2131.79
4	.9	T	233.10	930.32	2468.01	1078.49
		P	.01068	1.5937	.89312	.01068
		u	1226.39	160.428	926.747	2473.93
5	.9	T	233.10	1282.07	2648.30	869.38
		P	.01068	5.8482	3.3793	.01068
		u	1532.99	219.559	960.582	2746.91
6	.9	T	233.10	1686.03	2856.12	725.96
		P	.01068	18.9347	11.3067	.01068
		u	1839.59	286.507	999.087	2991.08
7	.9	T	233.10	2133.37	3090.81	625.65
		P	.01068	55.2726	34.1319	.01068
		u	2146.19	359.196	1041.90	3225.35
8	.9	T	233.10	2614.16	3352.45	553.55
		P	.01068	148.475	94.7234	.01068
		u	2452.79	435.125	1088.74	3458.56
9	.9	T	233.10	3122.75	3642.73	500.82
		P	.01068	373.861	245.895	.01068
		u	2759.38	512.635	1139.59	3694.67
10	.9	T	233.10	3658.82	3963.42	460.17
		P	.01068	890.315	602.269	.01068
		u	3065.98	591.352	1194.33	3935.68

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit.

Hydrogen Fuel at T_f = 300 K ---- Isentropic Diffuser

Table 53
Temperature, Pressure and Velocity
At Four Ramjet Stations

M_F	M_c		i	DE	c	e
1	.9	T	233.10	278.45	2104.37	2109.15
		P	.01068	.01981	.01043	.01068
		u	306.598	48.998	858.447	841.742
2	.9	T	392.39	415.83	2181.41	1903.01
		P	.04809	.05895	.03147	.01068
		u	229.388	72.836	873.185	1479.49
3	.9	T	617.77	637.75	2272.47	1736.41
		P	.11082	.12477	.06810	.01068
		u	234.890	111.689	891.918	1829.23
4	.9	T	912.59	929.90	2378.10	1671.95
		P	.19971	.21511	.12081	.01068
		u	256.719	163.333	914.663	2055.15
5	.9	T	1268.95	1280.82	2494.44	1672.02
		P	.31539	.32784	.19047	.01068
		u	282.548	226.322	940.858	2246.17
6	.9	T	1680.62	1682.73	2616.99	1719.98
		P	.45823	.46078	.27834	.01068
		u	309.078	300.223	969.983	2423.57
7	.9	T	2134.10	2121.29	2741.98	1804.63
		P	.62901	.61086	.38522	.01068
		u	333.733	383.648	1001.64	2594.23
8	.9	T	2580.15	2551.86	2867.26	1912.92
		P	.83015	.77729	.51147	.01068
		u	351.001	469.147	1035.74	2760.61
9	.9	T	2957.69	2918.43	2991.85	2029.62
		P	1.0639	.96421	.65709	.01068
		u	358.31	546.199	1072.33	2923.23
10	.9	T	3275.66	3225.88	3115.50	2134.30
		P	1.3287	1.16999	.82010	.01068
		u	361.549	616.004	1111.59	3091.60

i-inlet DE-diffuser exit c-combustion chamber exit
e-nozzle exit

<u>Hydrogen Fuel at</u> T_f = 300 K ---- <u>Normal Shock Diffuser</u>

Table 54

Ramjet Performance Parameters
Isentropic Diffuser, Propane Fuel T_f=230.9 K

M_F	M_c	F_s	F_{sfc}	η_{th}	η_p
1	.7	504.523	.4582	.0880	.5834
	.8	488.079	.4737	.0839	.5921
	.9	478.886	.4828	.0816	.5971
2	.7	960.447	.2407	.3277	.5964
	.8	955.774	.2419	.3253	.5977
	.9	953.301	.2425	.3241	.5983
3	.7	1142.34	.2024	.5290	.6559
	.8	1138.34	.2031	.5264	.6567
	.9	1136.05	.2035	.5249	.6572
4	.7	1177.91	.1963	.6597	.7179
	.8	1175.33	.1967	.6577	.7184
	.9	1173.80	.1970	.6565	.7187
5	.7	1152.59	.2006	.7435	.7719
	.8	1150.78	.2009	.7420	.7722
	.9	1149.68	.2011	.7410	.7724
6	.7	1103.05	.2096	.7982	.8166
	.8	1101.73	.2098	.7969	.8168
	.9	1100.94	.2100	.7962	.8169
7	.7	1046.26	.2210	.8348	.8528
	.8	1045.23	.2212	.8338	.8529
	.9	1044.61	.2213	.8331	.8530
8	.7	989.608	.2336	.8597	.8818
	.8	988.743	.2338	.8588	.8819
	.9	988.208	.2340	.8582	.8820
9	.7	936.354	.2469	.8767	.9051
	.8	935.611	.2471	.8758	.9052
	.9	935.155	.2472	.8753	.9053
10	.7	887.012	.2606	.8873	.9240
	.8	886.309	.2609	.8864	.9241
	.9	885.869	.2610	.8858	.9241

F_s - Specific Thrust (N·s/Kg)

F_{sfc} - Thrust Specific Fuel Consumption (Kg_f/hour/N)

η_{th} - Thermodynamic Efficiency η_p - Propulsive Efficiency

Table 55

Ramjet Performance Parameters

Normal Shock Diffuser, Propane Fuel T_f=230.9 K

M_F	M_c	F_s	F_{sfc}	η_{th}	η_p
1	.7	504.524	.4582	.0880	.5834
	.8	488.079	.4737	.0839	.5921
	.9	478.885	.4827	.0816	.5971
2	.7	839.061	.2755	.2697	.6313
	.8	833.916	.2772	.2673	.6329
	.9	830.367	.2784	.2657	.6340
3	.7	852.052	.2713	.3534	.7262
	.8	846.267	.2732	.3501	.7278
	.9	835.765	.2766	.3443	.7306
4	.7	772.405	.2993	.3779	.8073
	.8	767.632	.3012	.3749	.8085
	.9	764.942	.3022	.3732	.8092
5	.7	661.969	.3493	.3656	.8718
	.8	657.892	.3514	.3628	.8728
	.9	655.623	.3526	.3612	.8733
6	.7	539.788	.4283	.3251	.9224
	.8	536.138	.4312	.3224	.9232
	.9	534.037	.4329	.3208	.9236
7	.7	411.686	.5616	.2589	.9617
	.8	408.365	.5662	.2563	.9622
	.9	406.484	.5688	.2547	.9626
8	.7	279.639	.8268	.1679	.9899
	.8	276.640	.8357	.1653	.9903
	.9	274.953	.8409	.1638	.9905
9	.7	144.966	1.5948	.0524	.9988
	.8	142.197	1.6259	.0499	.9985
	.9	140.611	1.6442	.0484	.9984
10	.7	18.464	12.521	-.0773	.7910
	.8	16.264	14.215	-.0794	.7649
	.9	14.990	15.423	-.0807	.7472

F_s - Specific Thrust (N·s/Kg)

F_{sfc} - Thrust Specific Fuel Consumption (Kg_f/hour/N)

η_{th} - Thermodynamic Efficiency η_p - Propulsive Efficiency

Table 56

Ramjet Performance Parameters

Isentropic Diffuser, Hydrogen Fuel T_f=20 K

M_F	M_c	F_s	F_{sfc}	η_{th}	η_p
1	.7	539.510	.1959	.0856	.5475
	.8	528.705	.1999	.0831	.5527
	.9	518.721	.2038	.0808	.5576
2	.7	1021.51	.1035	.3160	.5615
	.8	1022.19	.1034	.3163	.5613
	.9	1025.35	.1031	.3177	.5606
3	.7	1242.04	.0851	.5258	.6144
	.8	1237.72	.0854	.5232	.6152
	.9	1235.24	.0856	.5217	.6157
4	.7	1282.16	.0824	.6560	.6758
	.8	1279.41	.0826	.6541	.6763
	.9	1277.80	.0827	.6530	.6766
5	.7	1254.20	.0843	.7397	.7303
	.8	1252.29	.0844	.7382	.7306
	.9	1251.16	.0845	.7373	.7308
6	.7	1198.10	.0882	.7942	.7761
	.8	1196.70	.0883	.7931	.7763
	.9	1195.88	.0884	.7924	.7765
7	.7	1132.27	.0933	.8306	.8140
	.8	1131.15	.0934	.8296	.8141
	.9	1130.49	.0935	.8290	.8142
8	.7	1064.87	.0993	.8547	.8451
	.8	1063.89	.0993	.8537	.8452
	.9	1063.29	.0994	.8531	.8453
9	.7	998.836	.1058	.8692	.8707
	.8	997.877	.1059	.8682	.8709
	.9	997.320	.1060	.8677	.8709
10	.7	934.778	.1131	.8752	.8921
	.8	933.641	.1132	.8740	.8922
	.9	933.001	.1133	.8733	.8923

F_s- Specific Thrust (N·s/kg)

F_{sfc}- Thrust Specific Fuel Consumption (Kg_f/hour/N)

η_{th} - Thermodynamic Efficiency η_p - Propulsive Efficiency

Table 57

Ramjet Performance Parameters

Normal Shock Diffuser, Hydrogen Fuel T_f=20 K

M_F	M_c	F_s	F_{sfc}	η_{th}	η_p
1	.7	539.580	.1959	.0856	.5475
	.8	528.706	.1999	.0831	.5527
	.9	518.813	.2037	.0808	.5575
2	.7	890.216	.1187	.2590	.5963
	.8	891.539	.1186	.2596	.5960
	.9	895.660	.1180	.2613	.5948
3	.7	938.352	.1126	.3570	.6815
	.8	932.183	.1134	.3538	.6830
	.9	928.691	.1138	.3520	.6838
4	.7	862.341	.1226	.3892	.7613
	.8	857.235	.1233	.3862	.7624
	.9	854.320	.1237	.3846	.7631
5	.7	752.098	.1405	.3875	.8260
	.8	747.730	.1414	.3848	.8270
	.9	745.281	.1418	.3832	.8275
6	.7	628.834	.1681	.3608	.8782
	.8	624.939	.1691	.3582	.8789
	.9	622.722	.1697	.3567	.8794
7	.7	499.155	.2117	.3120	.9206
	.8	495.562	.2133	.3094	.9213
	.9	493.512	.2142	.3079	.9217
8	.7	365.003	.2896	.2416	.9555
	.8	361.777	.2921	.2391	.9561
	.9	359.959	.2936	.2377	.9564
9	.7	227.061	.4655	.1495	.9837
	.8	224.004	.4718	.1470	.9842
	.9	222.242	.4756	.1455	.9844
10	.7	89.332	1.813	.0387	.9999
	.8	86.921	1.216	.0366	.9999
	.9	85.537	1.236	.0354	.9999

F_s - Specific Thrust (N·s/Kg)

F_{sfc} - Thrust Specific Fuel Consumption (Kg_f/hour/N)

η_{th} - Thermodynamic Efficiency η_p - Propulsive Efficiency

Table 58

Ramjet Performance Parameters

Isentropic Diffuser, Hydrogen Fuel T_f= 300 K

M_F	M_c	F_s	F_{sfc}	η_{th}	η_p
1	.7	543.889	.1943	.0866	.5454
	.8	549.736	.1923	.0880	.5427
	.9	559.866	.1889	.0904	.5380
2	.7	1079.56	.0979	.3427	.5474
	.8	1072.50	.0985	.3394	.5491
	.9	1043.44	.1013	.3260	.5561
3	.7	1281.20	.0825	.5494	.6067
	.8	1277.03	.0828	.5469	.6075
	.9	1274.59	.0829	.5454	.6079
4	.7	1324.40	.0798	.6855	.6683
	.8	1321.73	.0800	.6837	.6687
	.9	1320.17	.0801	.6826	.6690
5	.7	1297.48	.0815	.7733	.7320
	.8	1295.65	.0816	.7718	.7233
	.9	1294.56	.0816	.7710	.7235
6	.7	1241.41	.0851	.8309	.7693
	.8	1240.09	.0852	.8298	.7695
	.9	1239.31	.0853	.8291	.7696
7	.7	1175.46	.0899	.8700	.8076
	.8	1174.47	.0900	.8691	.8077
	.9	1173.85	.0900	.8685	.8078
8	.7	1108.57	.0953	.8974	.8390
	.8	1107.81	.0954	.8967	.8391
	.9	1107.31	.0955	.8962	.8391
9	.7	1044.77	.1012	.9173	.8647
	.8	1044.15	.1012	.9166	.8648
	.9	1043.76	.1013	.9162	.8648
10	.7	986.042	.1072	.9323	.8857
	.8	985.574	.1072	.9317	.8858
	.9	985.244	.1073	.9314	.8858

F_s- Specific Thrust (N·s/Kg)

F_{sfc}- Thrust Specific Fuel Consumption (Kg_f/hour/N)

η_{th} - Thermodynamic Efficiency η_p- Propulsive Efficiency

Table 59
Ramjet Performance Parameters
Normal Shock Diffuser, Hydrogen Fuel T_f=300 K

τ	M_c	F_s	F_{sfc}	η_{th}	η_p
1	.7	543.648	.1943	.0866	.5454
	.8	549.731	.1923	.0880	.5427
	.9	559.857	.1888	.0904	.5380
2	.7	950.454	.1112	.2846	.5798
	.8	942.451	.1121	.2811	.5820
	.9	909.733	.1162	.2672	.5909
3	.7	972.434	.1087	.3747	.6732
	.8	966.487	.1094	.3716	.6746
	.9	963.145	.1097	.3698	.6754
4	.7	896.678	.1179	.4092	.7535
	.8	891.880	.1185	.4064	.7545
	.9	889.094	.1189	.4047	.7552
5	.7	785.671	.1345	.4089	.8188
	.8	781.502	.1352	.4062	.8197
	.9	779.125	.1357	.4047	.8202
6	.7	660.847	.1599	.3828	.8717
	.8	657.207	.1608	.3803	.8725
	.9	655.136	.1613	.3789	.8729
7	.7	529.414	.1996	.3343	.9149
	.8	526.115	.2009	.3318	.9155
	.9	524.204	.2016	.3304	.9159
8	.7	393.466	.2686	.2639	.9506
	.8	390.544	.2706	.2616	.9511
	.9	388.872	.2718	.2603	.9514
9	.7	253.892	.4163	.1717	.9797
	.8	251.238	.4207	.1695	.9801
	.9	249.667	.4233	.1682	.9803
10	.7	119.521	.8843	.0651	.9988
	.8	117.558	.8991	.0634	.9990
	.9	116.382	.9082	.0624	.9991

F_s - Specific Thrust (N·s/Kg)

F_{sfc} - Thrust Specific Fuel Consumption (Kg_f/hour/N)

η_{th} - Thermodynamic Efficiency η_p - Propulsive Efficiency

Table 60

Performance Parameters For A Propane* Ramjet With Isentropic Diffuser And Supersonic Combustion (altitude = 100000 f)

M_F	M_c		i	DE	c	e	F_s $\left(\frac{N\cdot s}{Kg}\right)$	F_{sfc} $\left(\frac{Kg}{hr\ N}\right)$	η_{th}	η_p	η_o
7	1.0	T	233.10	721.92	2875.3	1016.4	878.19	.2633	.6699	.8798	.6331
		P	.01068	.59986	4.8580	.01068					
		u	2146.2	1895.0	1050.4	2841.9					
8	1.0	T	233.10	1287.7	3186.5	770.79	915.86	.2524	.7804	.8926	.7546
		P	.01068	5.9563	28.827	.01068					
		u	2452.8	1923.7	1108.7	3165.4					
9	1.0	T	233.10	1876.7	3511.3	651.99	897.45	.2576	.8316	.9104	.8318
		P	.01068	30.597	106.97	.01068					
		u	2759.4	1954.8	1169.1	3436.2					
10	1.0	T	233.10	2472.6	3861.2	587.77	863.93	.2676	.8585	.9269	.8897
		P	.01068	112.57	307.67	.01068					
		u	3065.9	1995.0	1233.1	3692.8					

*T_f = 230.9 K i-inlet, DE-diffuser exit, c-combustion chamber exit, e-nozzle exit

Table 61
Performance Parameters For A Hydrogen*
Ramjet With Isentropic Diffuser And
Supersonic Combustion
(Altitude = 100000 f)

M_F	M_c		i	DE	c	e	F_s $\left(\frac{N \cdot s}{Kg}\right)$	F_{sfc} $\left(\frac{Kg}{hr\ N}\right)$	η_{th}	η_p	η_o
7	1.0	T	233.10	546.94	2840.2	1135.9	882.76	.1197	.6130	.8530	.5393
		P	.01068	.21557	2.5025	.01068					
		u	2146.2	1991.1	1117.8	2942.6					
8	1.0	T	233.10	1121.2	3154.7	785.77	966.71	.1093	.7605	.8591	.6750
		P	.01068	3.3650	20.148	.01068					
		u	2452.8	2024.1	1177.9	3321.9					
9	1.0	T	233.10	1725.0	3462.6	635.58	951.25	.1111	.8201	.8771	.7472
		P	.01068	20.955	82.487	.01068					
		u	2759.4	2052.5	1237.3	3604.8					
10	1.0	T	233.10	2345.1	3777.6	565.14	909.38	.1162	.8472	.8953	.7937
		P	.01068	86.859	234.58	.01068					
		u	3065.9	2083.3	1298.4	3861.9					

*T_f = 20 K   i-inlet, DE-diffuser exit, c-combustion chamber exit, e-nozzle exit

Table 62

Performance Parameters For A Hydrogen* Ramjet With Isentropic Diffuser And Supersonic Combustion (Altitude = 100000 f)

M_F	M_c		i	DE	c	e	F_s $\left(\frac{N \cdot s}{Kg}\right)$	F_{sfc} $\left(\frac{Kg}{hr\ N}\right)$	η_{th}	η_p	η_o
7	1.0	T	233.10	655.05	2907.3	1051.0	978.54	.1080	.6945	.8376	.5978
		P	.01068	.41746	3.9815	.01068					
		u	2146.2	1932.7	1131.0	3035.6					
8	1.0	T	233.10	1229.2	3213.5	754.69	1026.5	.1029	.8176	.8505	.7167
		P	.01068	4.9104	26.631	.01068					
		u	2452.8	1959.9	1189.5	3380.1					
9	1.0	T	233.10	1830.1	3522.9	612.77	1002.9	.1054	.8735	.8702	.7878
		P	.01068	27.302	105.72	.01068					
		u	2759.4	1985.5	1248.7	3655.0					
10	1.0	T	233.10	2440.8	3851.9	530.20	961.66	.1099	.9051	.8888	.8393
		P	.01068	105.60	326.73	.01068					
		u	3065.9	2017.6	1310.8	3912.8					

*T_f = 300 K   i- inlet, DE-diffuser exit, c-combustion chamber exit, e-nozzle exit

Table 63
Areas At Three Stations For A
Propane* Ramjet With Isentropic Diffuser
(Altitude = 100000 f)

(Thrust = 10000 Newtons)

M_F	M_c	$\dot{m}_{air}(\frac{Kg}{s})$	A_i (m^2)	A_{DE} (m^2)	A_e (m^2)
1	.7	19.8207	4.0137	16.4081	15.3004
2	.7	10.4118	1.0542	2.1340	3.4515
3	.7	8.7539	.5908	.3859	1.7122
4	.7	8.4896	.4298	.0897	1.1268
5	.7	8.6761	.3514	.0252	.8482
6	.7	9.0658	.3059	.0082	.6910
7	.7	9.5579	.2765	.0030	.5928
8	.7	10.1050	.2558	.0012	.5277
9	.7	10.6797	.2403	.0005	.4828
10	.7	11.2738	.2283	.0002	.4539

i-inlet DE-diffuser exit e-nozzle exit

*T_f=230.9 K

Table 64

Areas At Three Stations For A Hydrogen* Ramjet With Isentropic Diffuser (Altitude = 100000 f)

(Thrust = 10000 Newtons)

M_F	M_c	$\dot{m}_{air}(\frac{Kg}{s})$	A_i (m^2)	A_{DE} (m^2)	A_e (m^2)
1	.7	18.5353	3.7528	16.2188	15.2572
2	.7	9.7895	.9910	2.1202	3.4895
3	.7	8.0513	.5434	.3747	1.6446
4	.7	7.7993	.3948	.0868	1.0694
5	.7	7.9732	.3229	.0244	.7945
6	.7	8.3465	.2816	.0080	.6396
7	.7	8.8318	.2555	.0029	.5439
8	.7	9.3908	.2377	.0012	.4832
9	.7	10.0117	.2252	.0005	.4483
10	.7	10.6977	.2166	.0002	.4358

i-inlet DE-diffuser exit e-nozzle exit

*T_f = 20 K

Table 65
Areas At Four Stations For A
Hydrogen* Ramjet With Isentropic Diffuser
(Altitude = 100000 f)
(Thrust = 10000 Newtons)

M_F	M_c	$\dot{m}_{air}\left(\frac{Kg}{s}\right)$	A_i (m^2)	A_{DE} (m^2)	A_e (m^2)
1	.7	18.3861	3.7226	15.6832	15.4182
2	.7	9.2630	.9377	1.9571	3.2465
3	.7	7.8052	.5268	.3546	1.6193
4	.7	7.5506	.3822	.0821	1.0524
5	.7	7.7073	.3121	.0230	.7804
6	.7	8.0554	.2718	.0075	.6258
7	.7	8.5073	.2461	.0027	.5284
8	.7	9.0206	.2283	.0011	.4624
9	.7	9.5715	.2153	.0005	.4157
10	.7	10.1412	.2053	.0002	.3801

i-inlet DE-diffuser exit e-nozzle exit

*T_f = 300 K

Table 66
Ramjet Overall Efficiencies, η_o,
For Three Fuels
Isentropic Diffuser, Altitude = 100000 f

M_F	M_c	Hydrogen T_f=20 K	Hydrogen T_f=300 K	Propane T_f=230.9 K
1	.7	.0471	.0475	.0520
2	.7	.1783	.1884	.1978
3	.7	.3252	.3355	.3529
4	.7	.4476	.4624	.4852
5	.7	.5473	.5662	.5935
6	.7	.6274	.6501	.6816
7	.7	.6917	.7181	.7542
8	.7	.7435	.7740	.8153
9	.7	.7846	.8206	.8679
10	.7	.8158	.8606	.9135

Table 67

Ramjet Overall Efficiencies, η_o,
For Three Fuels
Normal Shock Diffuser, Altitude = 100000 f

M_F	M_c	Hydrogen T_f=20 K	Hydrogen T_f=300 K	Propane T_f=230.9 K
1	.7	.0471	.0475	.0520
2	.7	.1554	.1659	.1728
3	.7	.2457	.2546	.2632
4	.7	.3010	.3130	.3182
5	.7	.3282	.3429	.3409
6	.7	.3293	.3461	.3335
7	.7	.3049	.3234	.2968
8	.7	.2548	.2747	.2304
9	.7	.1784	.1994	.1344
10	.7	.0780	.1043	.0190

Table 68
Performance Of A Propane* Ramjet With
Isentropic Diffuser
As A Function Of Flight Altitude**
$M_c = .7$

Altitude (meters)	T_∞ (K)	P_∞ (Atm.)	$F_s \left(\frac{N \cdot s}{Kg}\right)$	$F_{sfc} \left(\frac{Kg}{hr\ N}\right)$	η_{th}	η_p	η_o
30480 (100000 f)	233.10	.01068	1177.91	.1963	.6597	.7179	.4852
20000	216.66	.05457	1205.48	.1918	.6807	.7125	.4966
15000	216.66	.11954	1206.73	.1916	.6817	.7123	.4971
10000	223.26	.26153	1198.07	.1930	.6750	.7140	.4935
5000	255.69	.53341	1155.50	.2000	.6427	.7223	.4760

$^*T_f = 230.9$ K
$^{**}u_\infty = 1226.39$ m/s

Table 69
Performance Of A Hydrogen* Ramjet With
Isentropic Diffuser
As A Function Of Flight Altitude**
$M_c = .7$

Altitude (meters)	T_∞ (K)	P_∞ (Atm.)	F_s $(\frac{N \cdot s}{Kg})$	F_{sfc} $(\frac{Kg}{hr\ N})$	η_{th}	η_p	η_o
30480 (100000 f)	233.10	.01068	1282.16	.0824	.6560	.6758	.4476
20000	216.66	.05457	1310.26	.0807	.6756	.6708	.4574
15000	216.66	.11954	1310.79	.0806	.6760	.6707	.4576
10000	223.26	.26153	1300.42	.0813	.6688	.6725	.4540
5000	255.69	.53341	1254.21	.0843	.6368	.6809	.4378

* $T_f = 20$ K

** $u_\infty = 1226.39$ m/s

Table 70

Performance Of A Hydrogen* Ramjet With Isentropic Diffuser As A Function Of Flight Altitude**

$M_c = .7$

Altitude (meters)	T_∞ (K)	P_∞ (Atm.)	$F_s \left(\frac{N \cdot s}{Kg}\right)$	$F_{sfc} \left(\frac{Kg}{hr\ N}\right)$	η_{th}	η_p	η_o
30480 (100000 f)	233.10	.01068	1324.40	.0798	.6855	.6683	.4624
20000	216.66	.05457	1354.37	.0780	.7069	.6630	.4728
15000	216.66	.11954	1355.88	.0780	.7079	.6627	.4733
10000	223.26	.26153	1347.09	.0785	.7016	.6643	.4703
5000	255.69	.53341	1301.68	.0812	.6696	.6723	.4544

* T_f = 300 K

** u_∞ = 1226.39 m/s

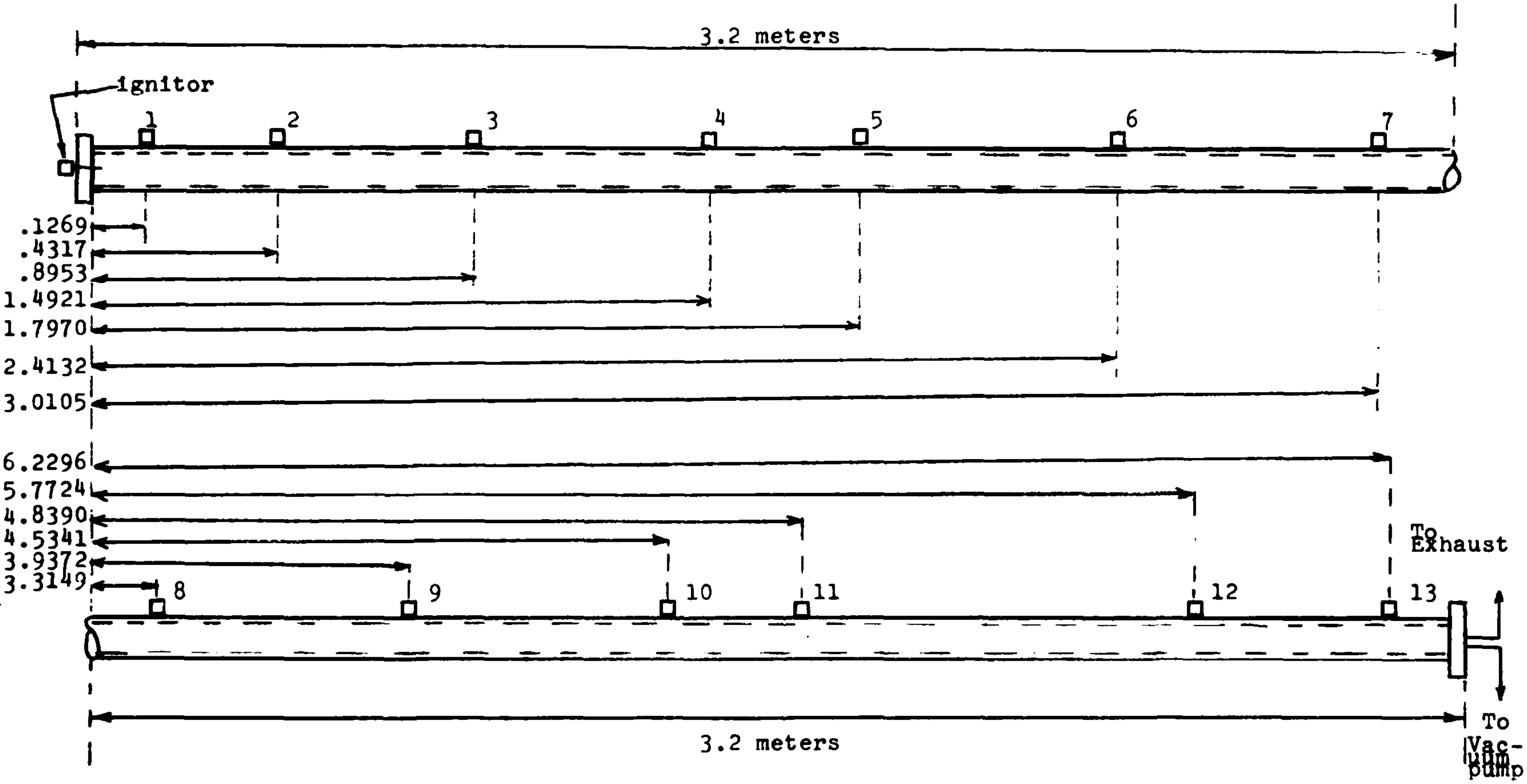
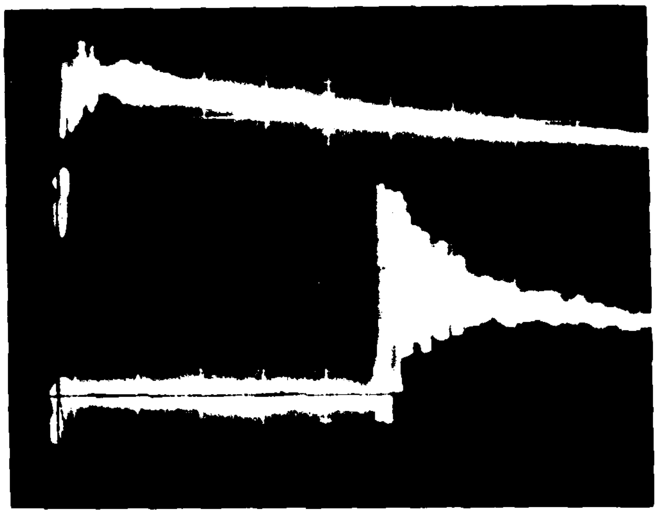


Figure 1
Combustion Tube Configuration
(Internal Diameter: 5 centimeters)

Figure 2

SAMPLE DATA PHOTOGRAPHS



$\frac{1}{2} O_2 + H_2 + He$

Position # 12

$P_{initial} = 2$ Atm.

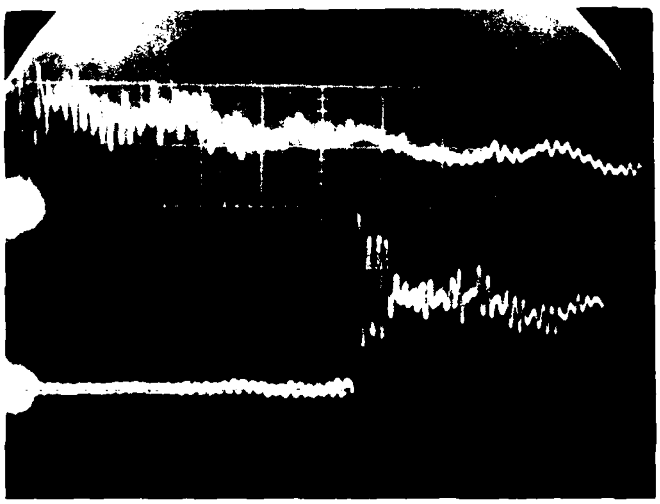
50 microsec./cm. (hor.)

.5 volts/cm. (ver.)

2 mv/pcb

Wave Speed = 3702 m/s

Wave pressure = 53.76 Atm.



$\frac{1}{2} O_2 + H_2 + N_2$

Position #8

$P_{initial} = 2$ Atm.

20 microsec./cm. (hor.)

1 volt/cm. (ver.)

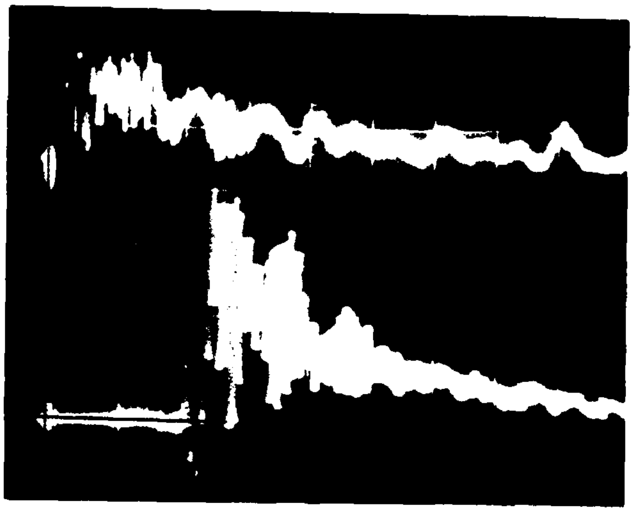
2 mv/pcb

Wave Speed = 2703 m/s

Wave Pressure = 48 Atm.

Figure 3

SAMPLE DATA PHOTOGRAPHS



$\frac{1}{2} O_2 + H_2 + Ar$

Position # 8

$P_{initial}$ = .5 Atm.

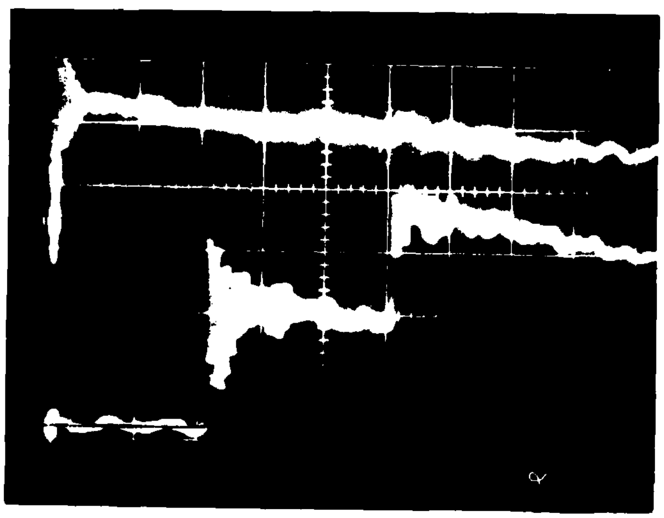
50 microsec./cm. (hor.)

2 volts/cm. (ver.)

20 mv/pcb

Wave Speed = 2696 m/s

Wave Pressure = 21.42 Atm.



$\frac{1}{2} O_2 + H_2 + He$

Position # 13

$P_{initial}$ = 2 Atm.

50 microsec./cm. (hor.)

1 volt/cm. (ver.)

2 mv/pcb

Wave Speed = 2998 m/s

Wave Pressure = 75.94 Atm.

(Note additional jump in second trace due to reflected wave from end of tube.)

Figure 4
Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$
$P_1 = .5$ Atm. $T_1 = 300$ K

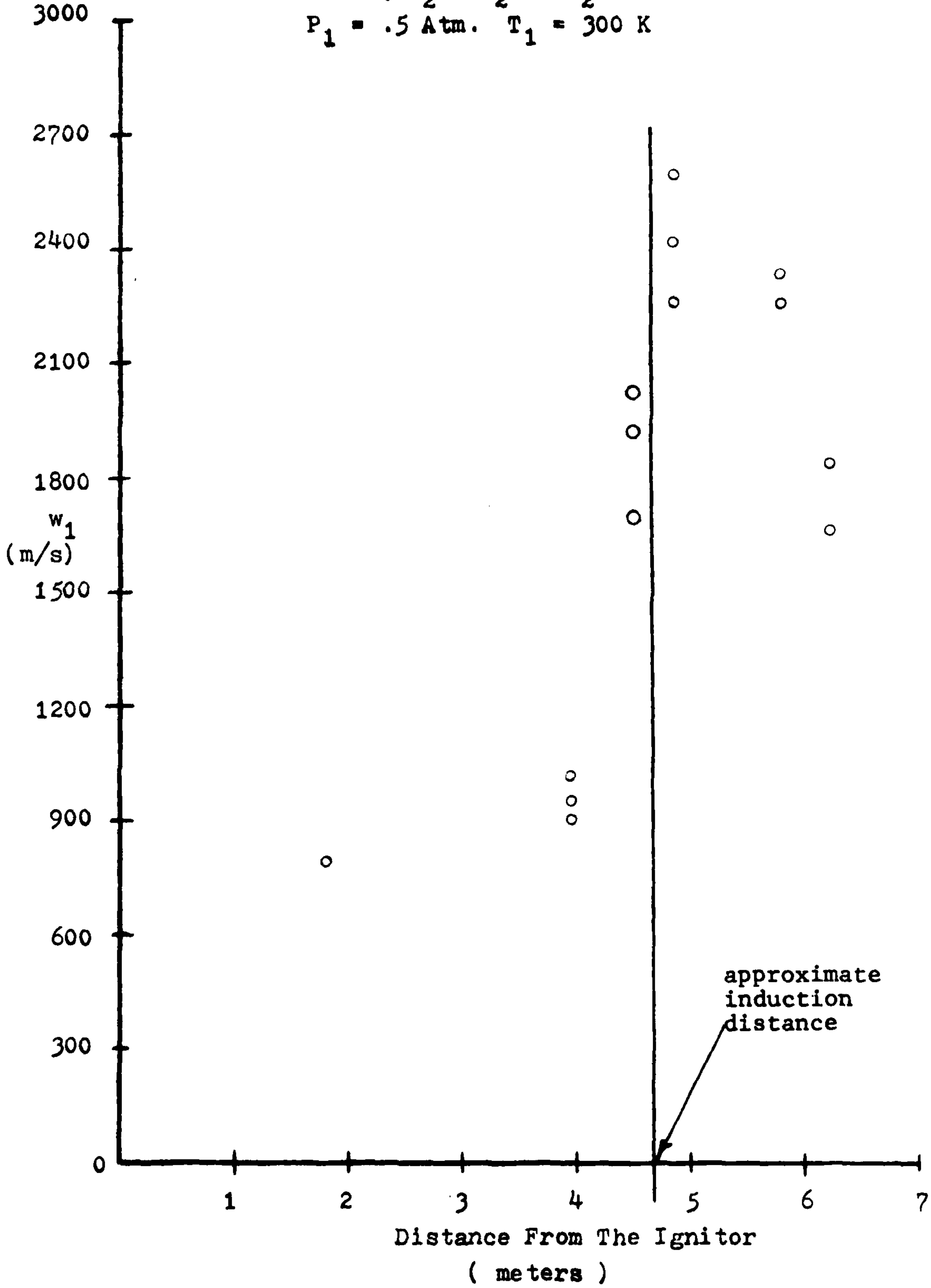


Figure 5
Wave Pressure Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$
$P_1 = .5$ Atm. $T_1 = 300$ K

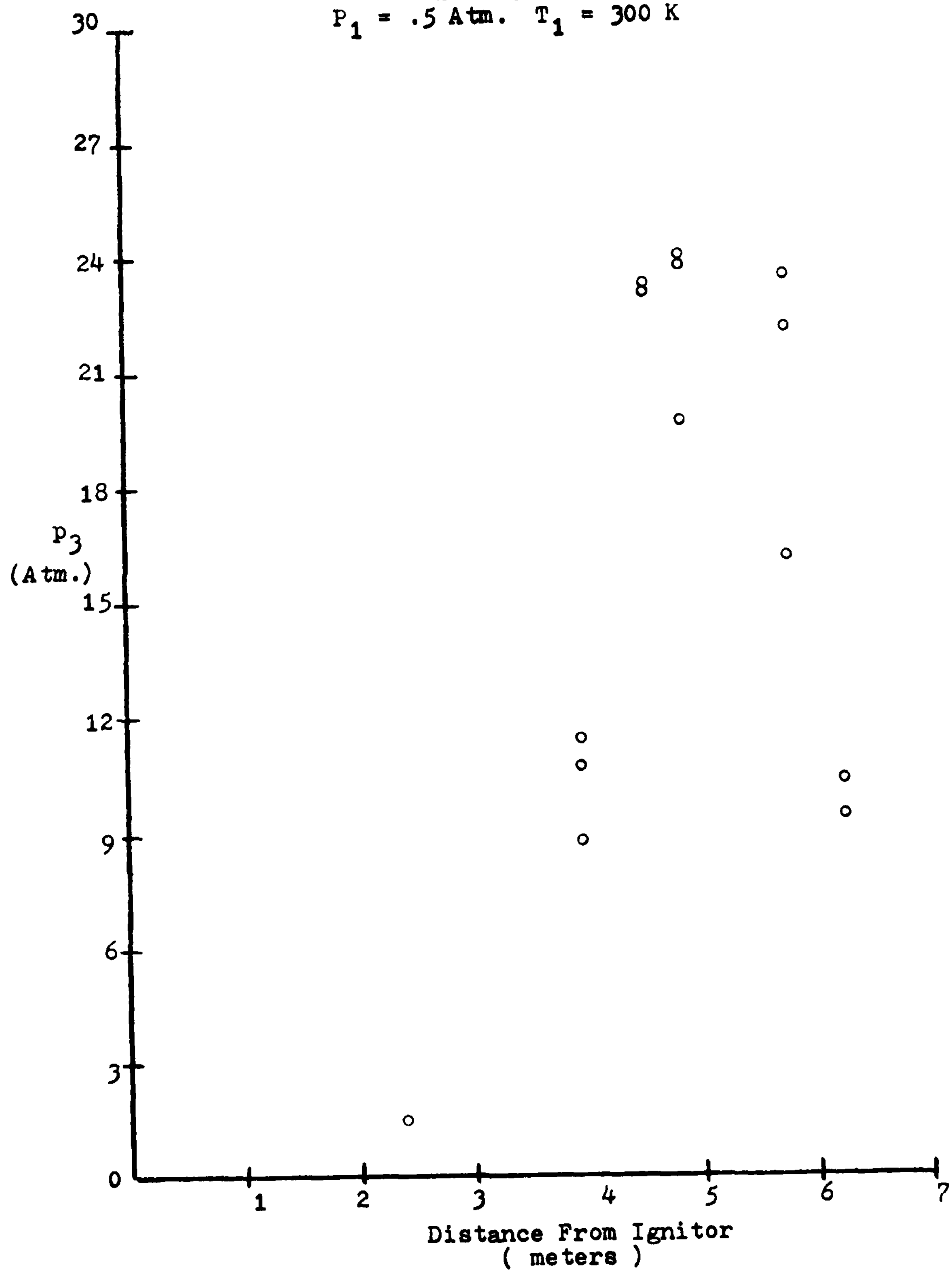


Figure 6
Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$
P_1 = 1 Atm. T_1 = 300 K

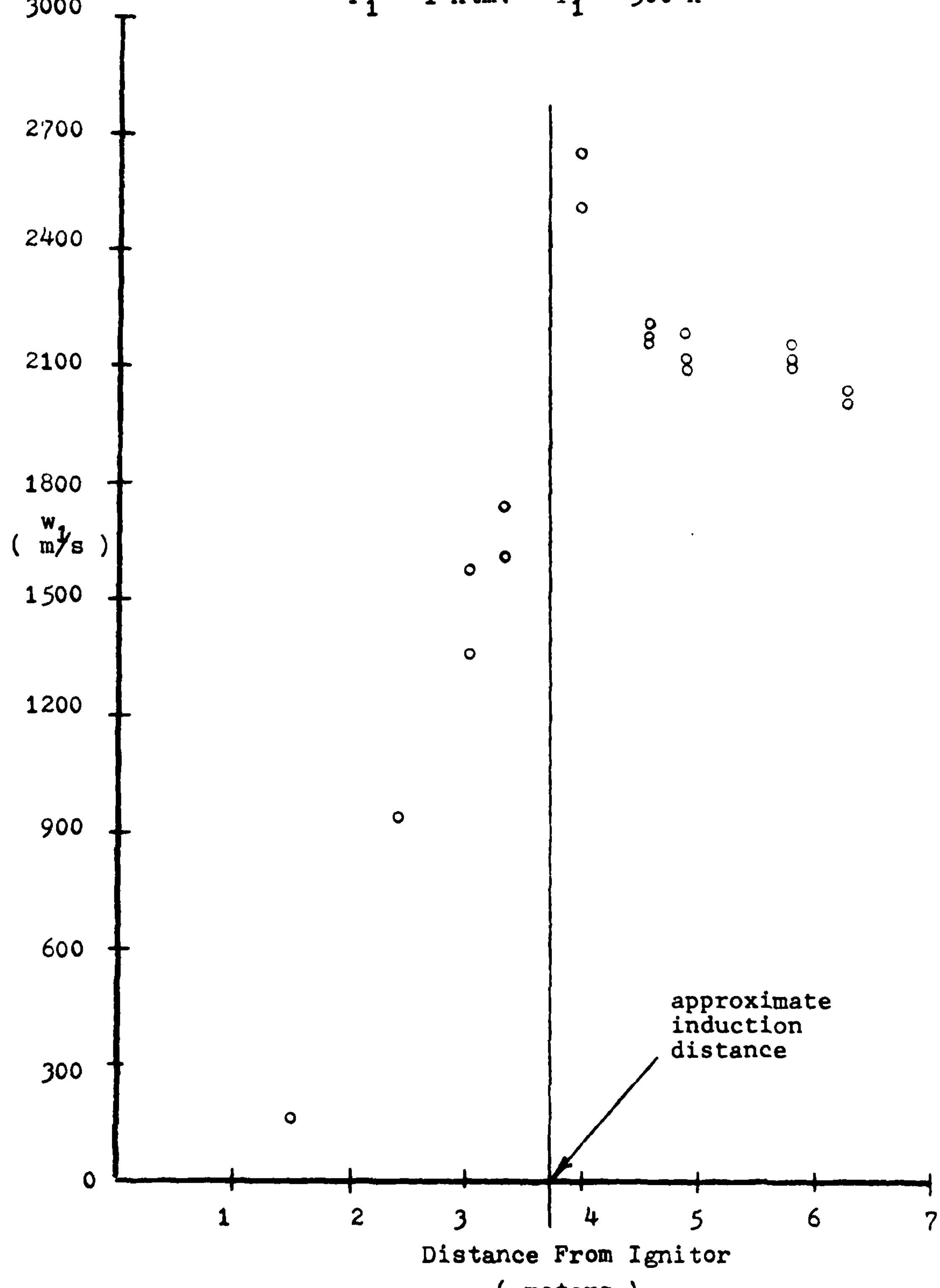


Figure 7
Wave Pressure Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$
P_1 = 1 Atm. T_1 = 300 K

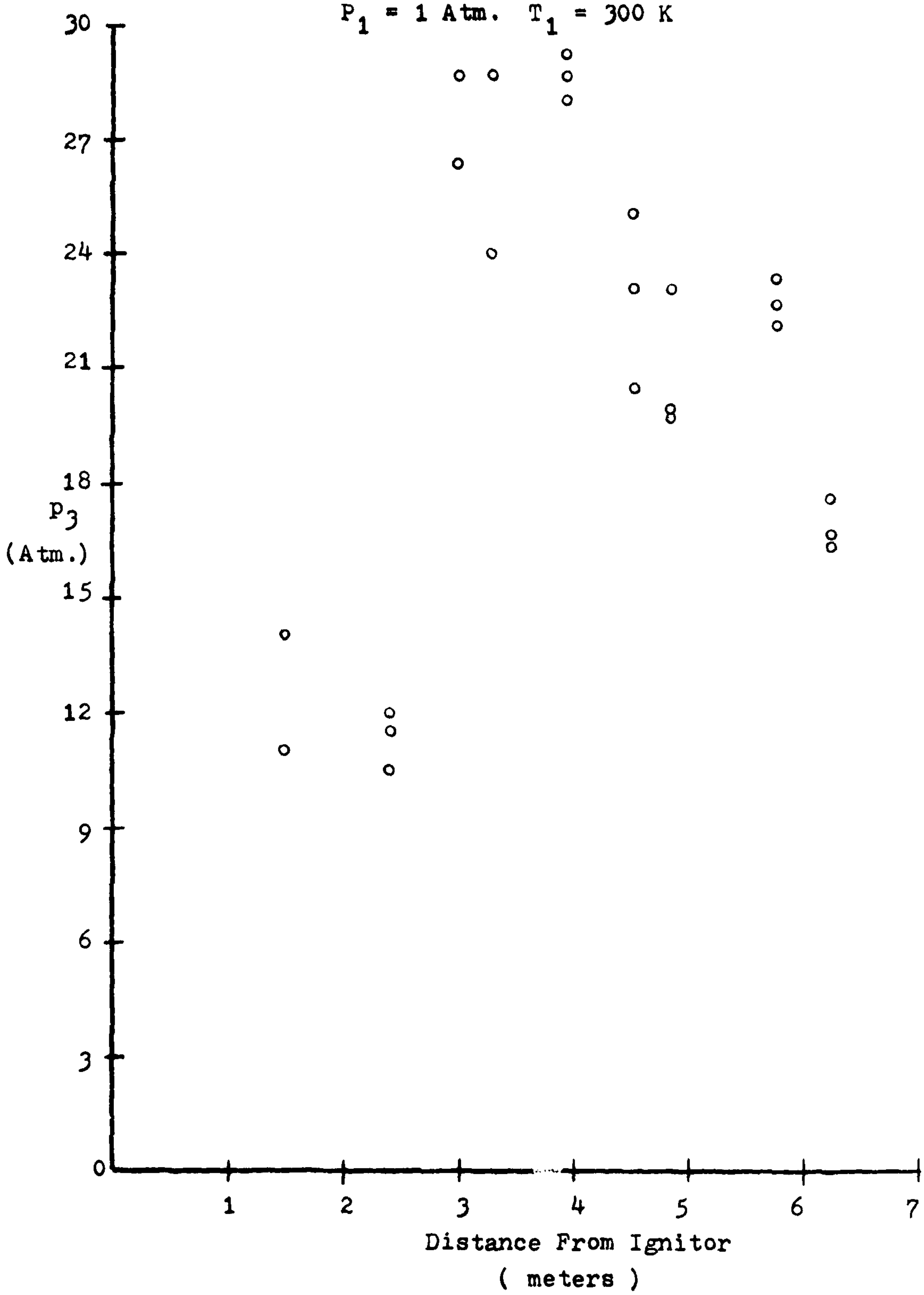


Figure 8
Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$
$P_1 = 2$ Atm. $T_1 = 300$ K

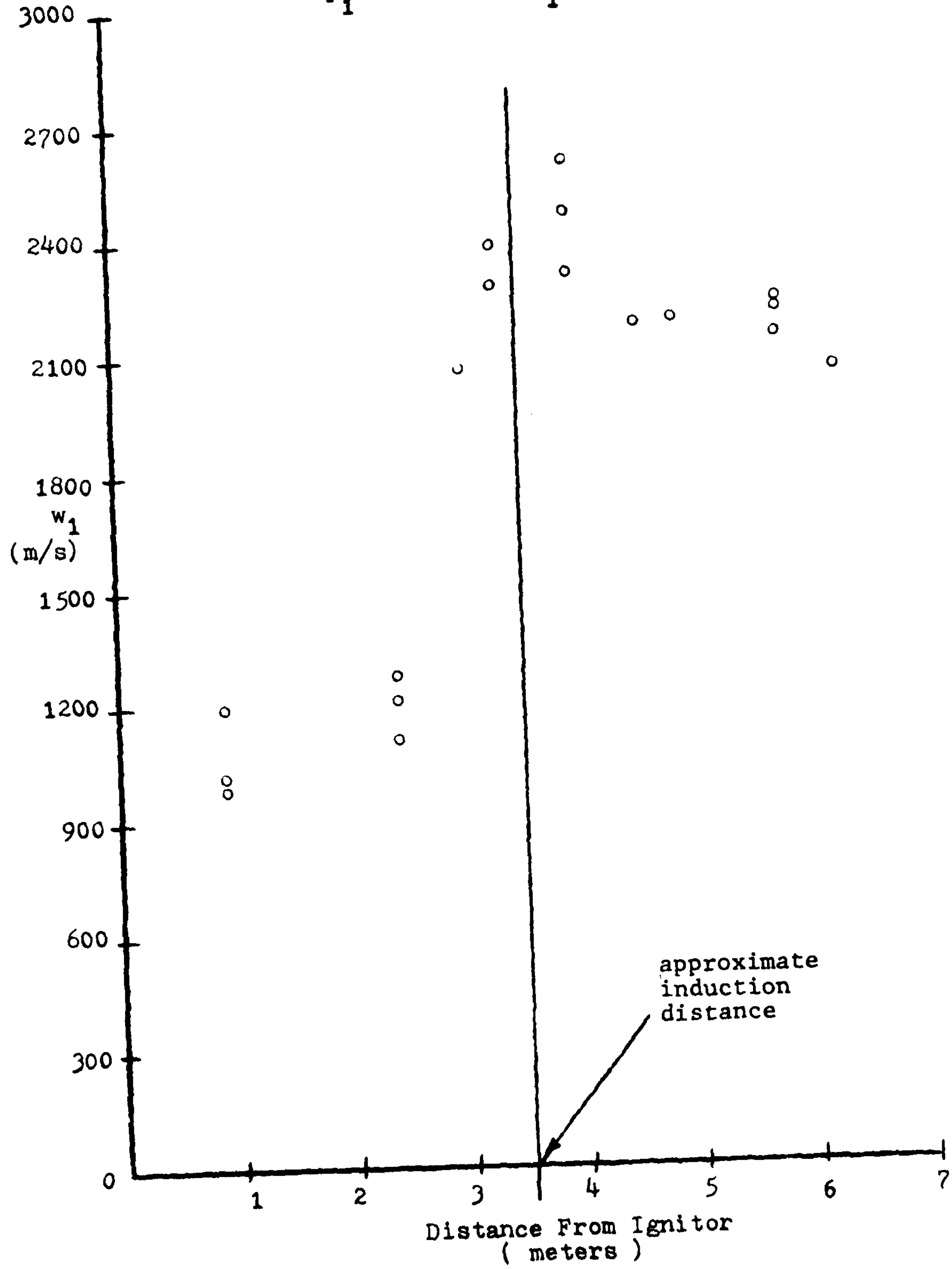


Figure 9
Wave Pressure Vs.
Distance From Ignitor

$\frac{1}{2} O_2 + H_2 + \frac{1}{2} CO_2$

$P_1 = 2$ Atm. $T_1 = 300$ K

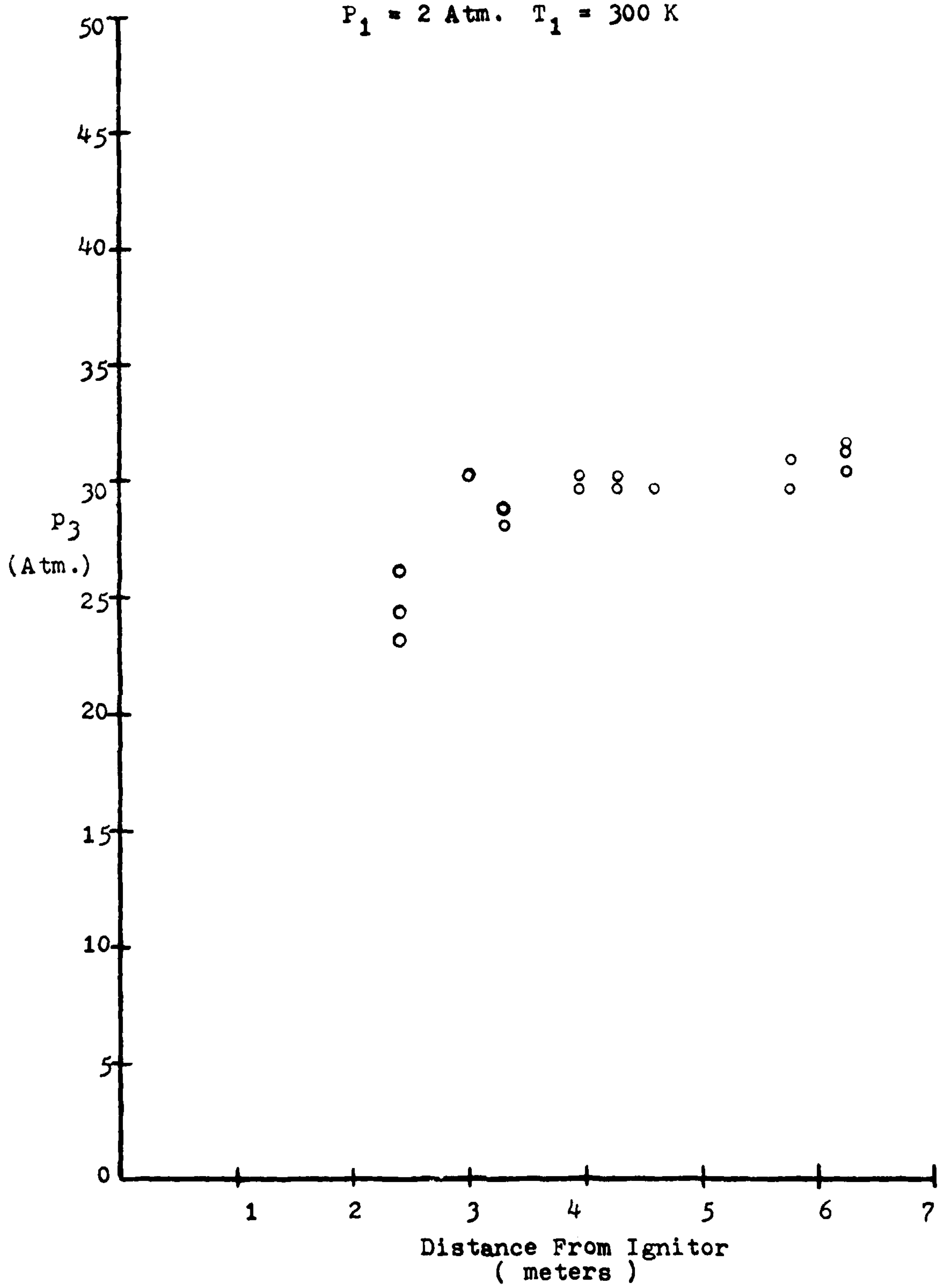


Figure 10
Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + N_2$
$P_1 = .5$ Atm. $T_1 = 300$ K

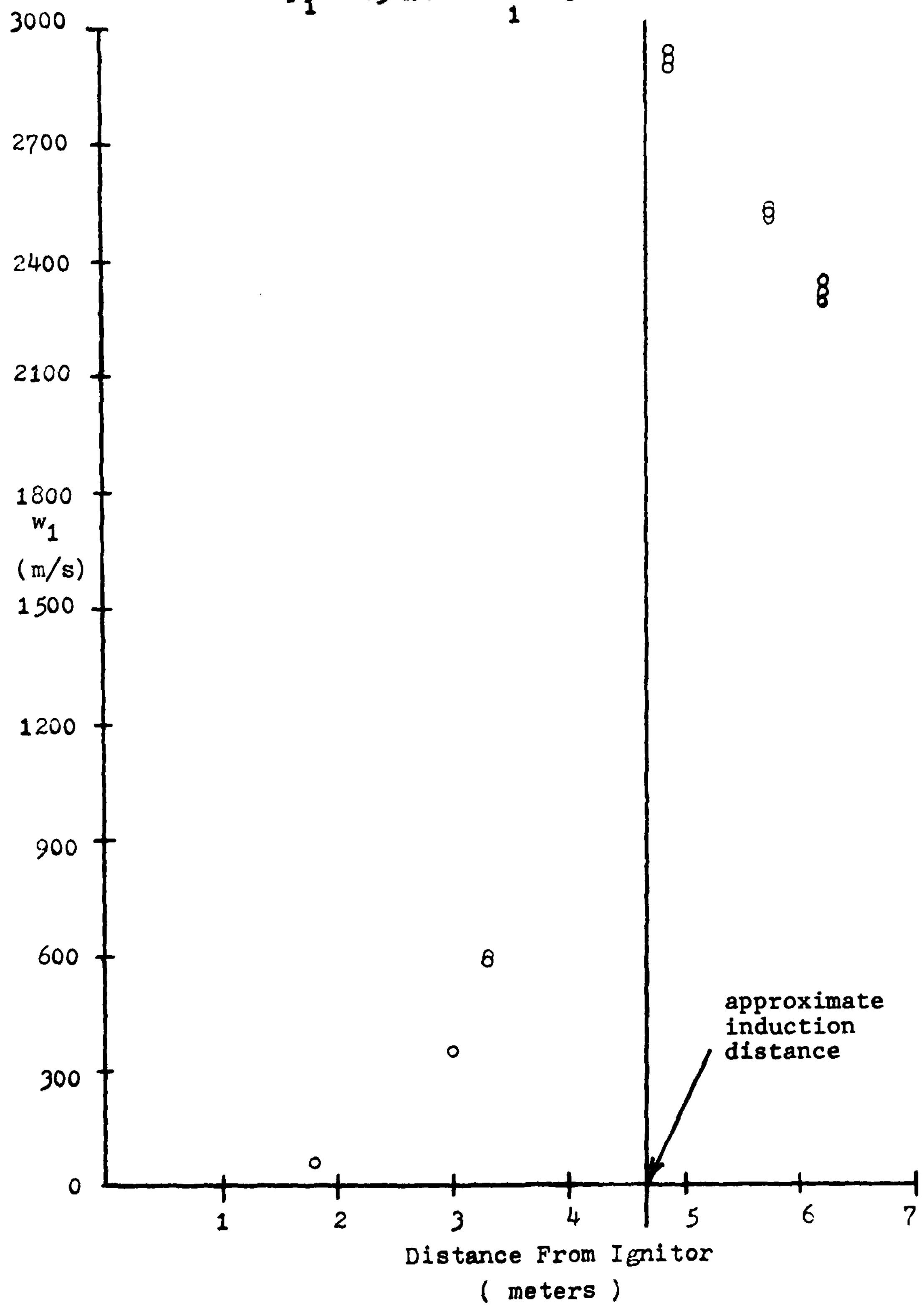


Figure 11

Wave Pressure Vs.

Distance From Ignitor

$\frac{1}{2} O_2 + H_2 + N_2$

$P_1 = .5$ Atm. $T_1 = 300$ K

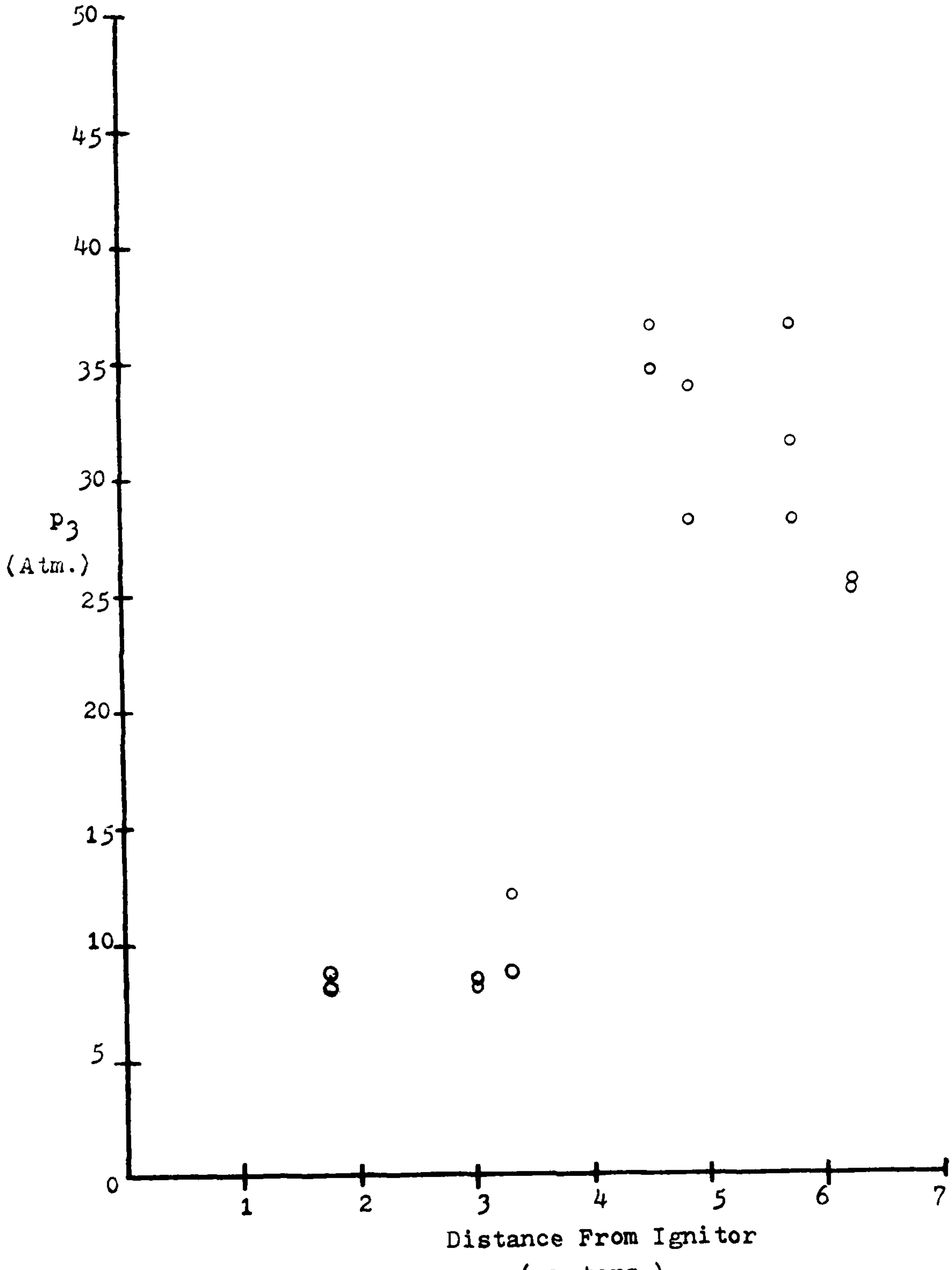


Figure 12
Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + N_2$
$P_1 = 1$ Atm. $T_1 = 300$ K

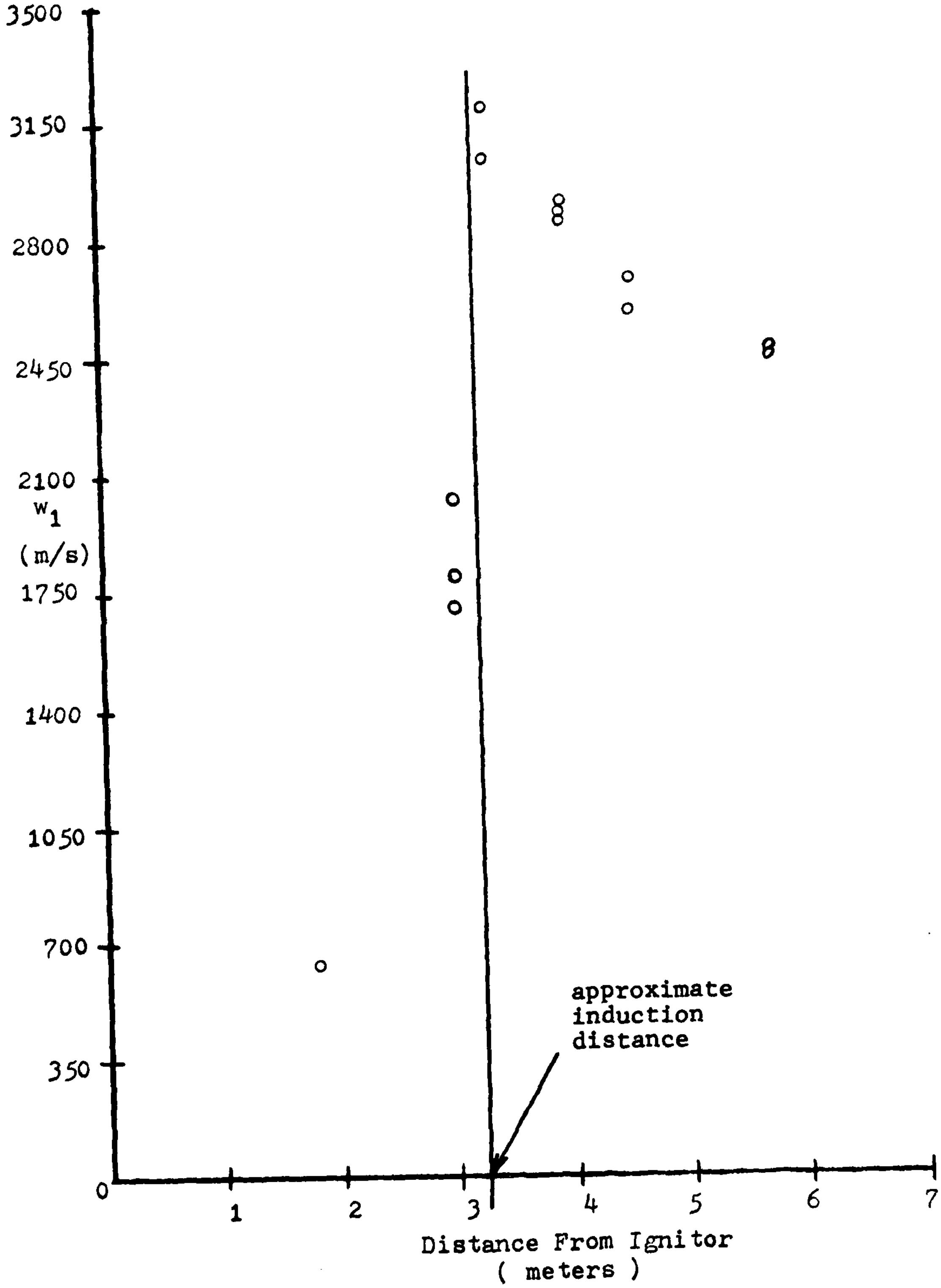


Figure 13
Wave Pressure Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + N_2$
P_1 = 1 Atm. T_1 = 300 K

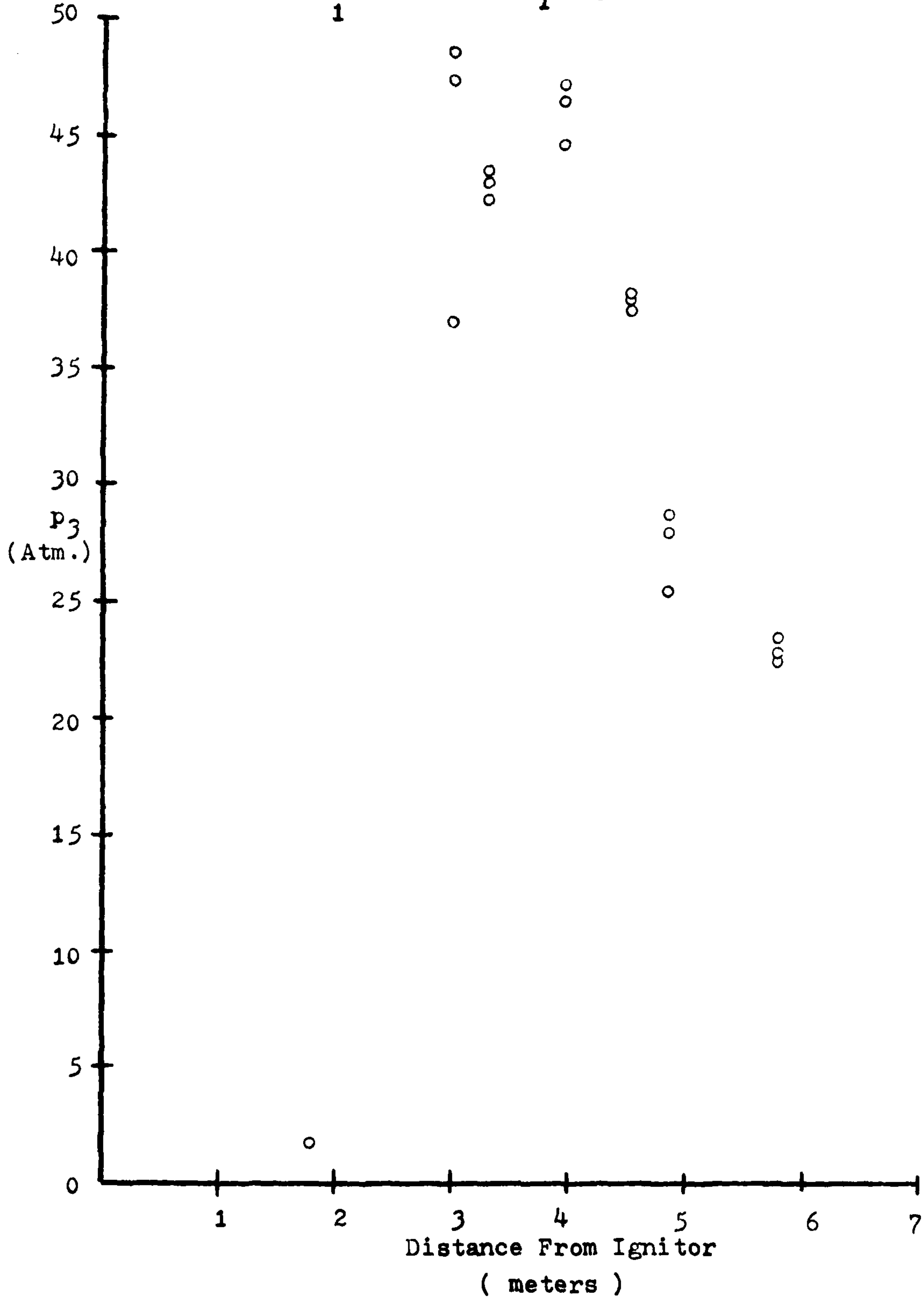


Figure 14
Wave Pressures Vs.
Distance From Ignitor
$\frac{1}{2}\, O_2 + H_2 + N_2$
$P_1 = 2$ Atm. $T_1 = 300$ K

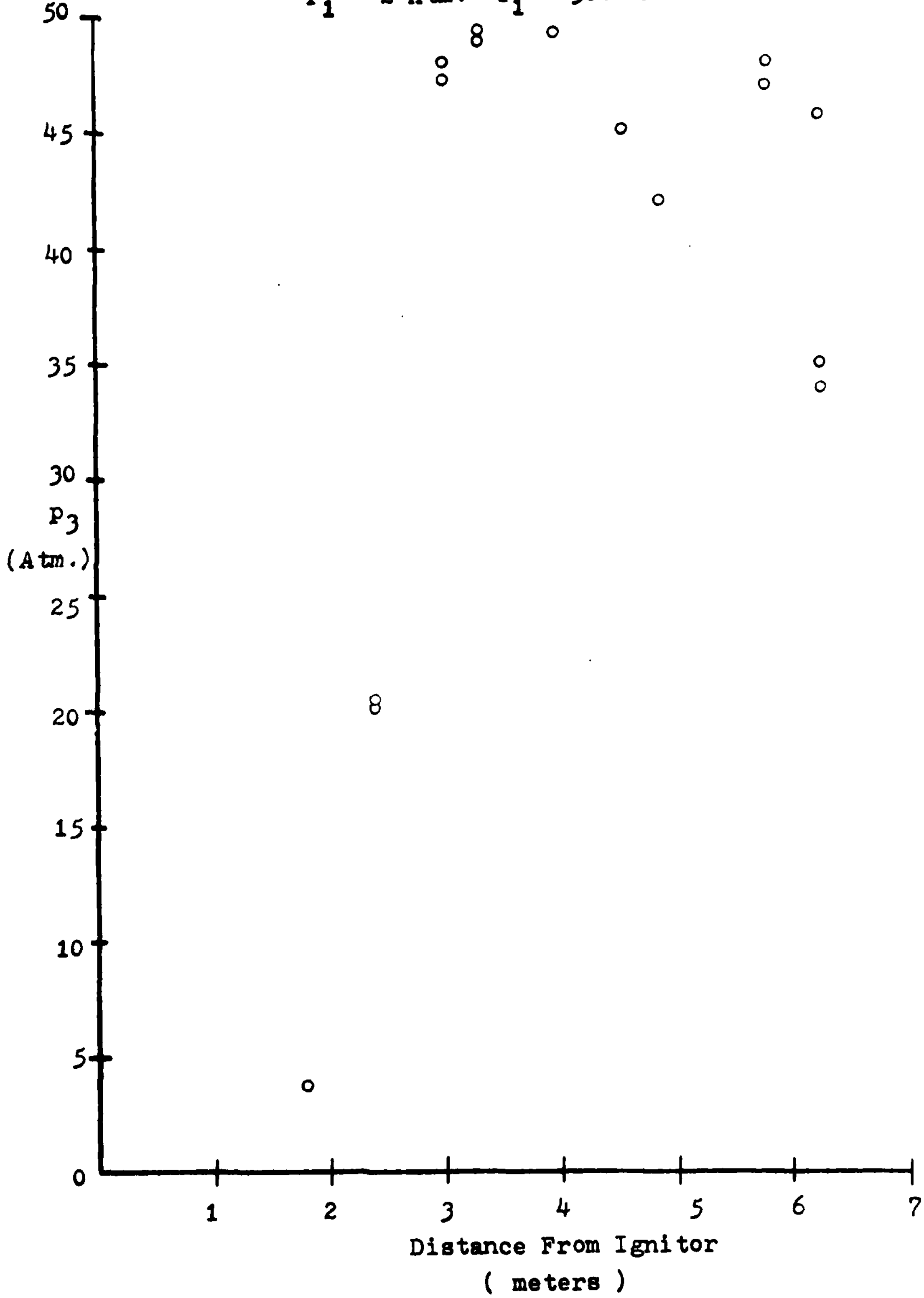


Figure 15

Wave Velocity Vs.
Distance From Ignitor

$\frac{1}{2}\,O_2 + H_2 + N_2$

$P_1 = 2$ Atm. $T_1 = 300$ K

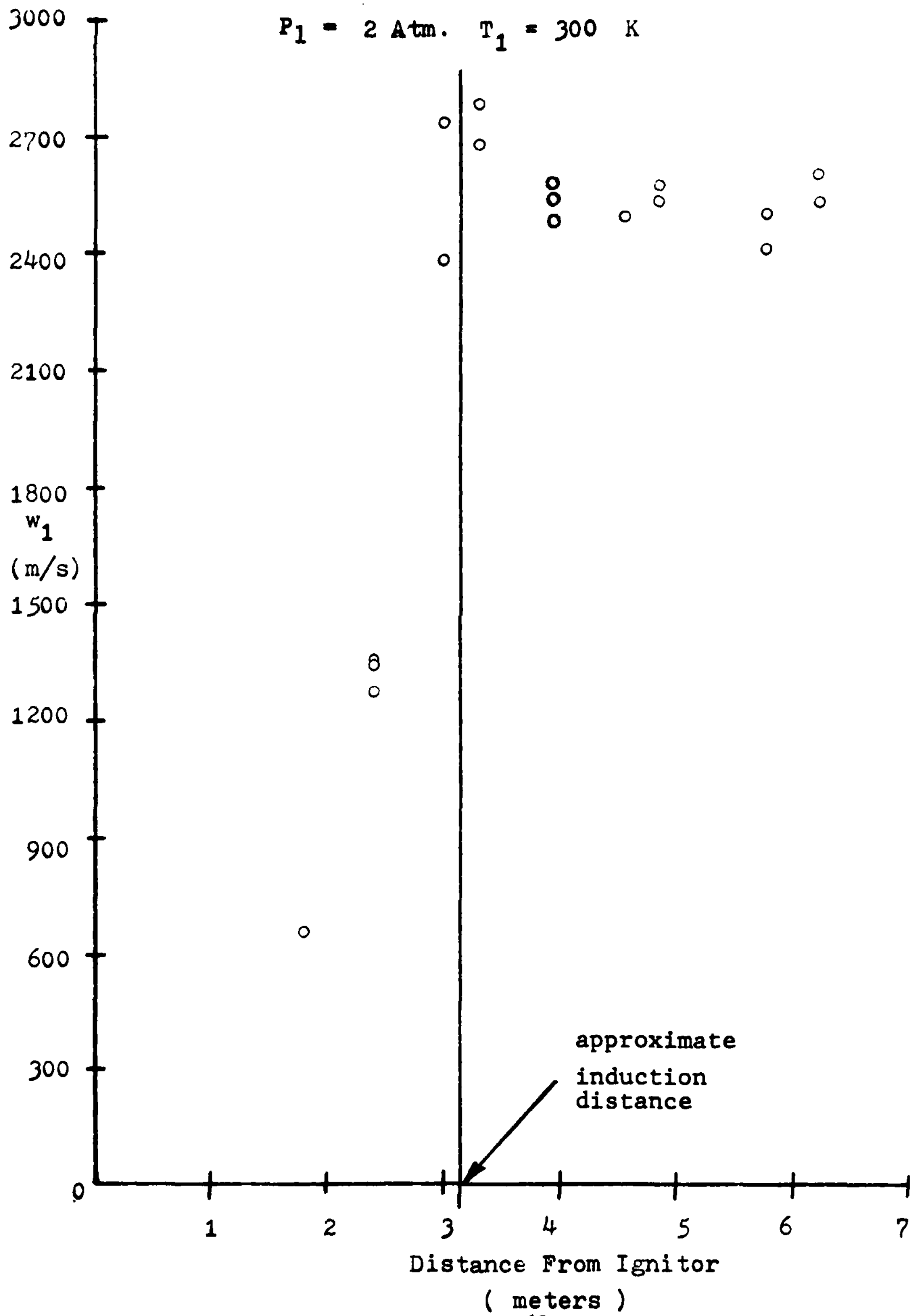


Figure 16
Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2}\ O_2 + H_2 + He$
$P_1 = .5$ Atm. $T_1 = 300$ K

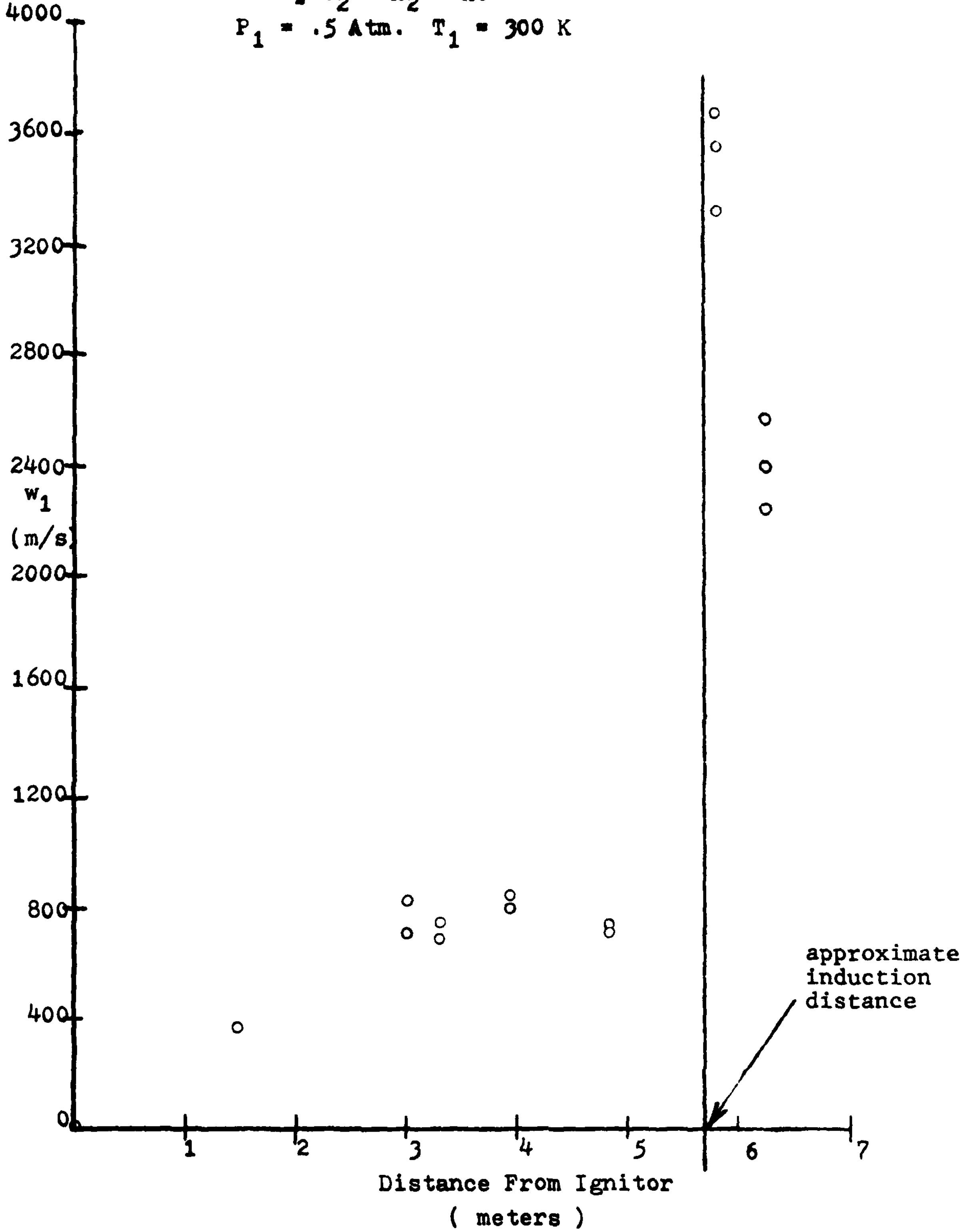


Figure 17

Wave Pressure Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + He$
$P_1 = .5$ Atm; $T_1 = 300$ K

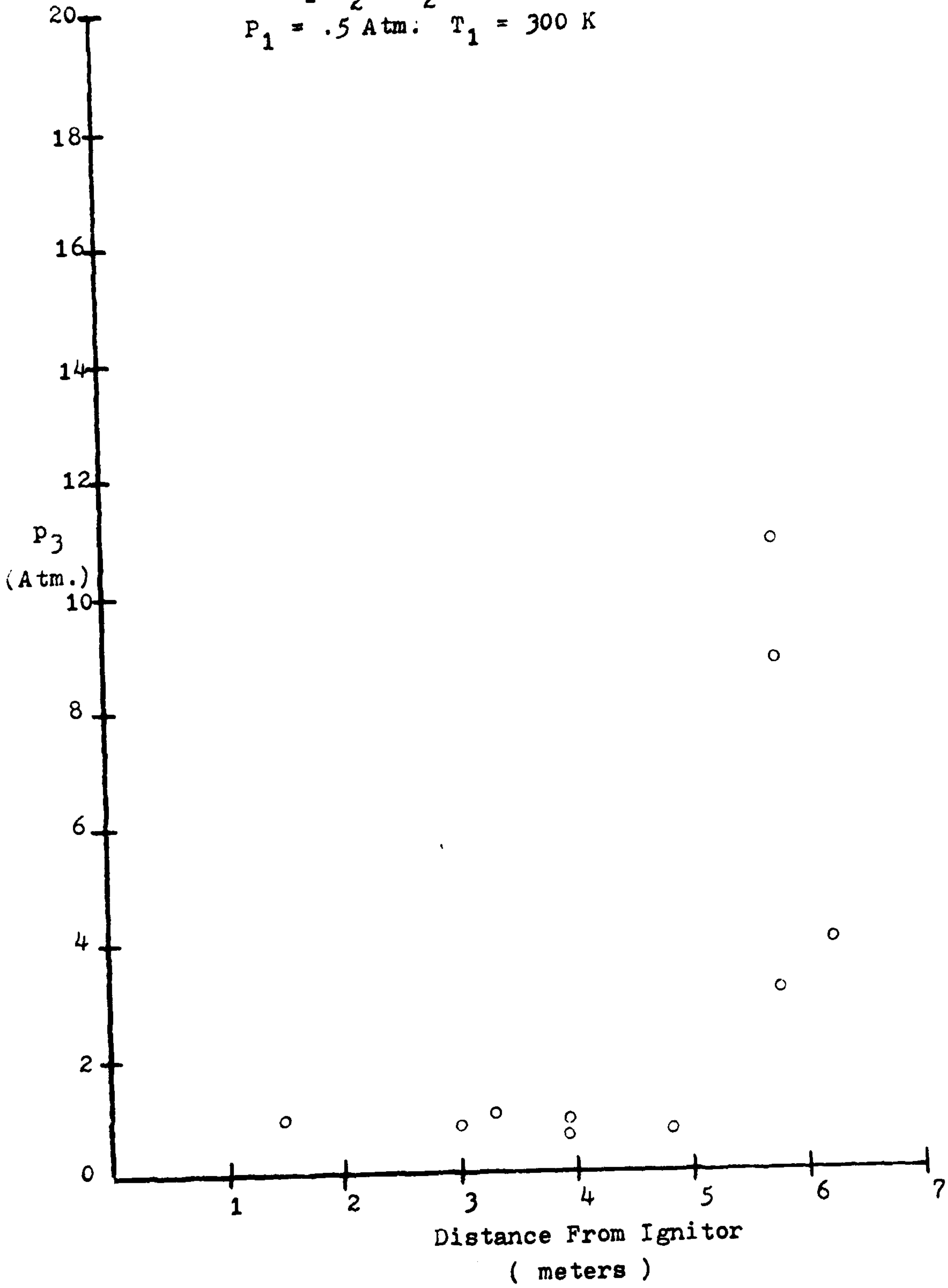


Figure 18

Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + He$
P_1 = 1 Atm. T_1 = 300 K

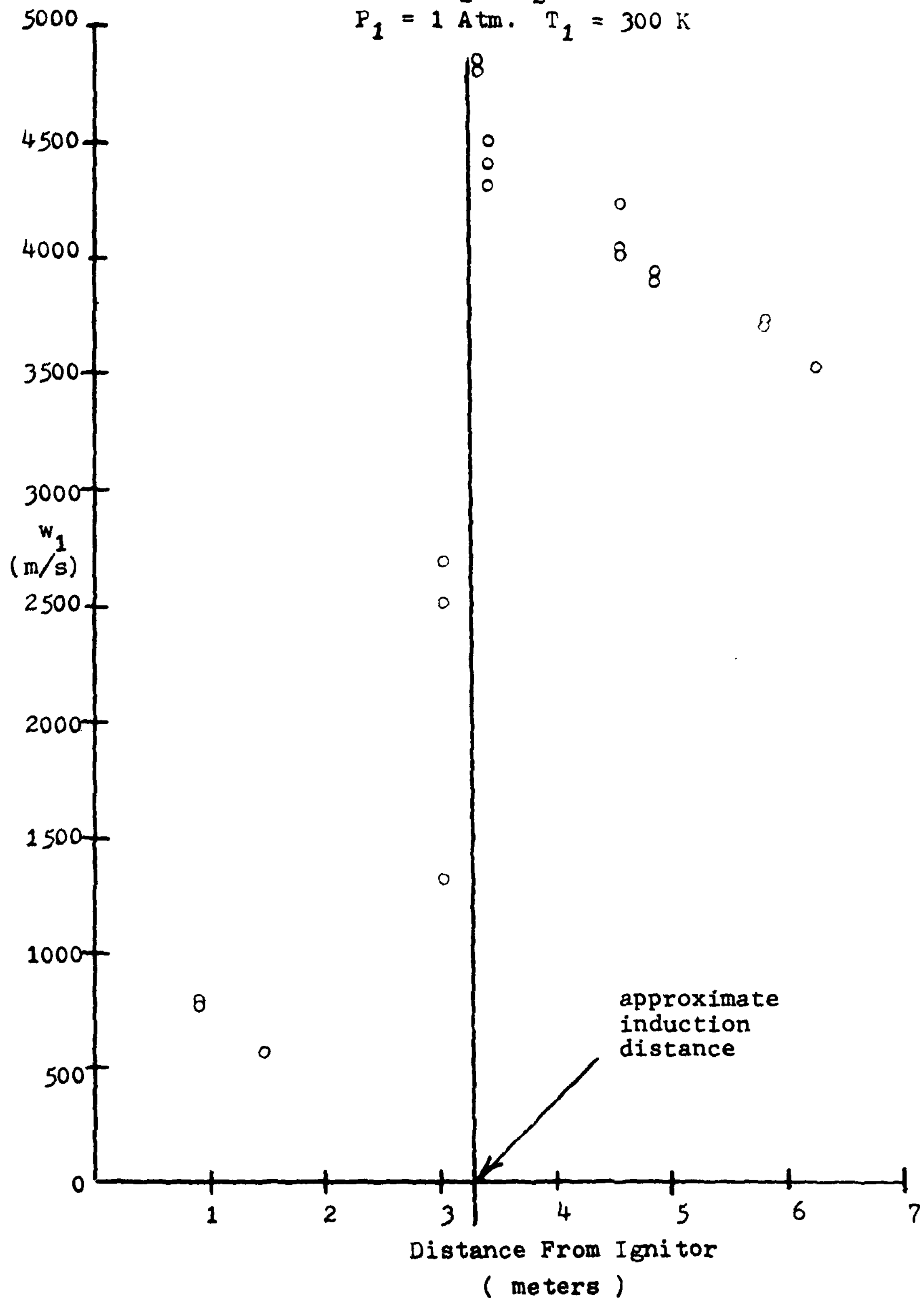


Figure 19
Wave Pressure Vs.
Distance From Ignitor
$\frac{1}{2}\ O_2 + H_2 + He$
$P_1 = 1$ Atm. $T_1 = 300$ K

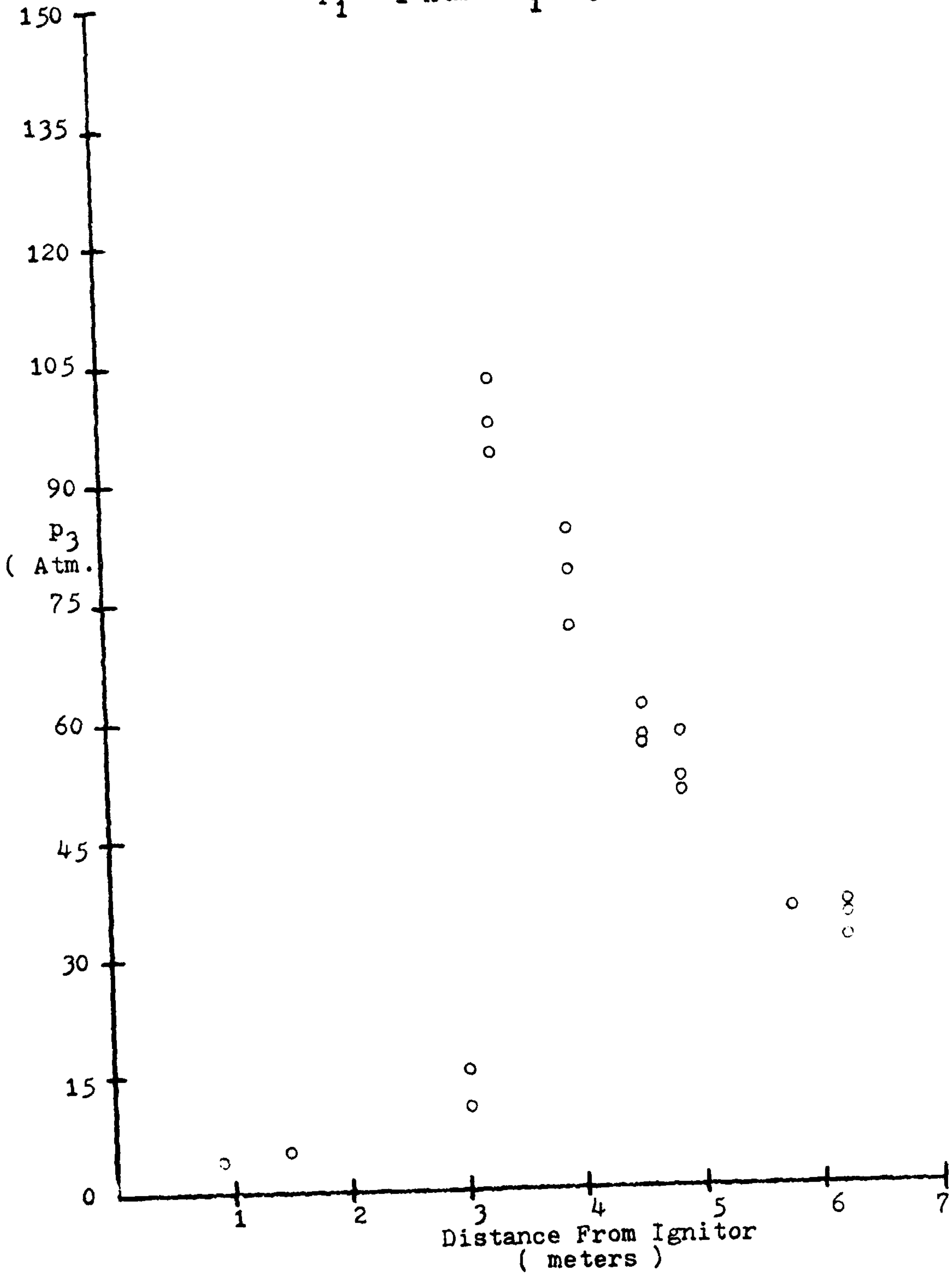
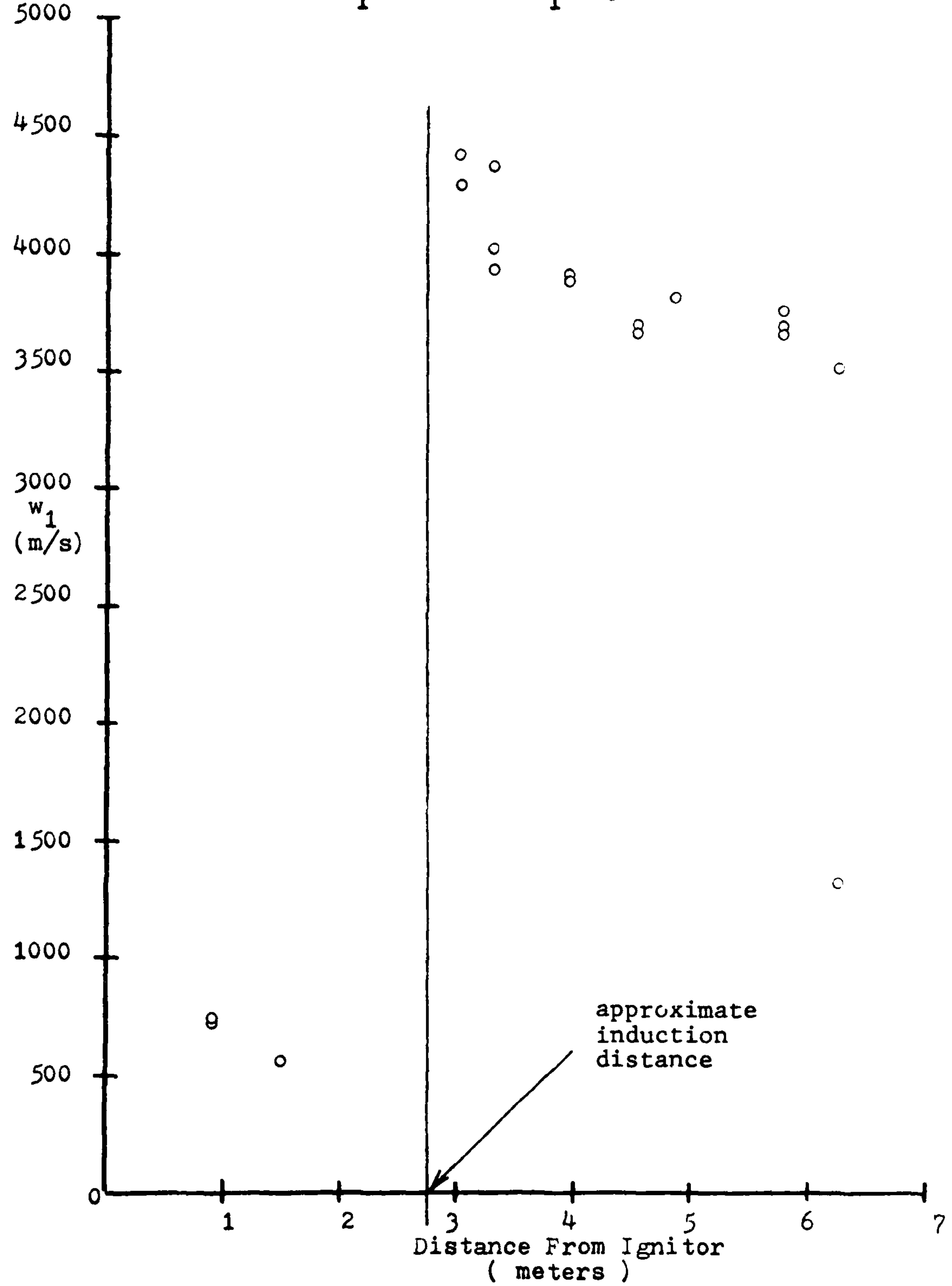


Figure 20
Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2}\ O_2 + H_2 + He$
$P_1 = 2$ Atm. $T_1 = 300$ K



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IGNITION, COMBUSTION, DETONATION AND HEAT ADDITION TO ESTABLISH--ETC(U)
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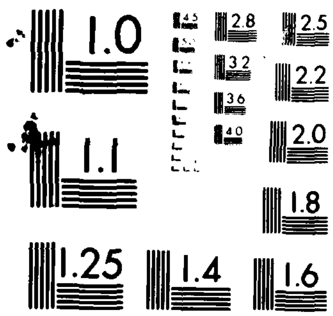


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

Figure 21
Wave Pressure Vs.
Distance From Ignitor
$\frac{1}{2}O_2 + H_2 + He$
$P_1 = 2$ Atm. $T_1 = 300$ K

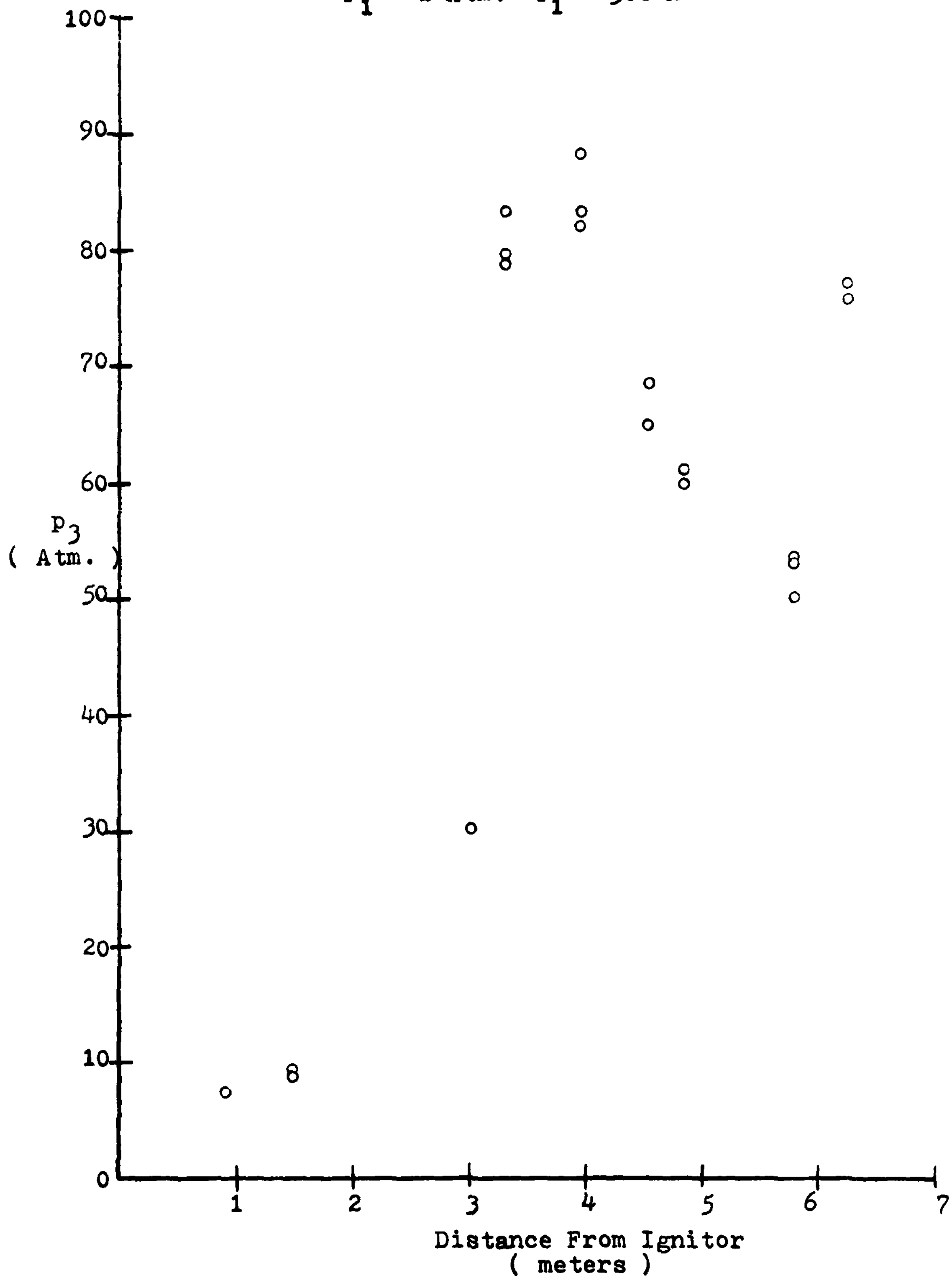


Figure 22

Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + Ar$
$P_1 = .5$ Atm. $T_1 = 300$ K

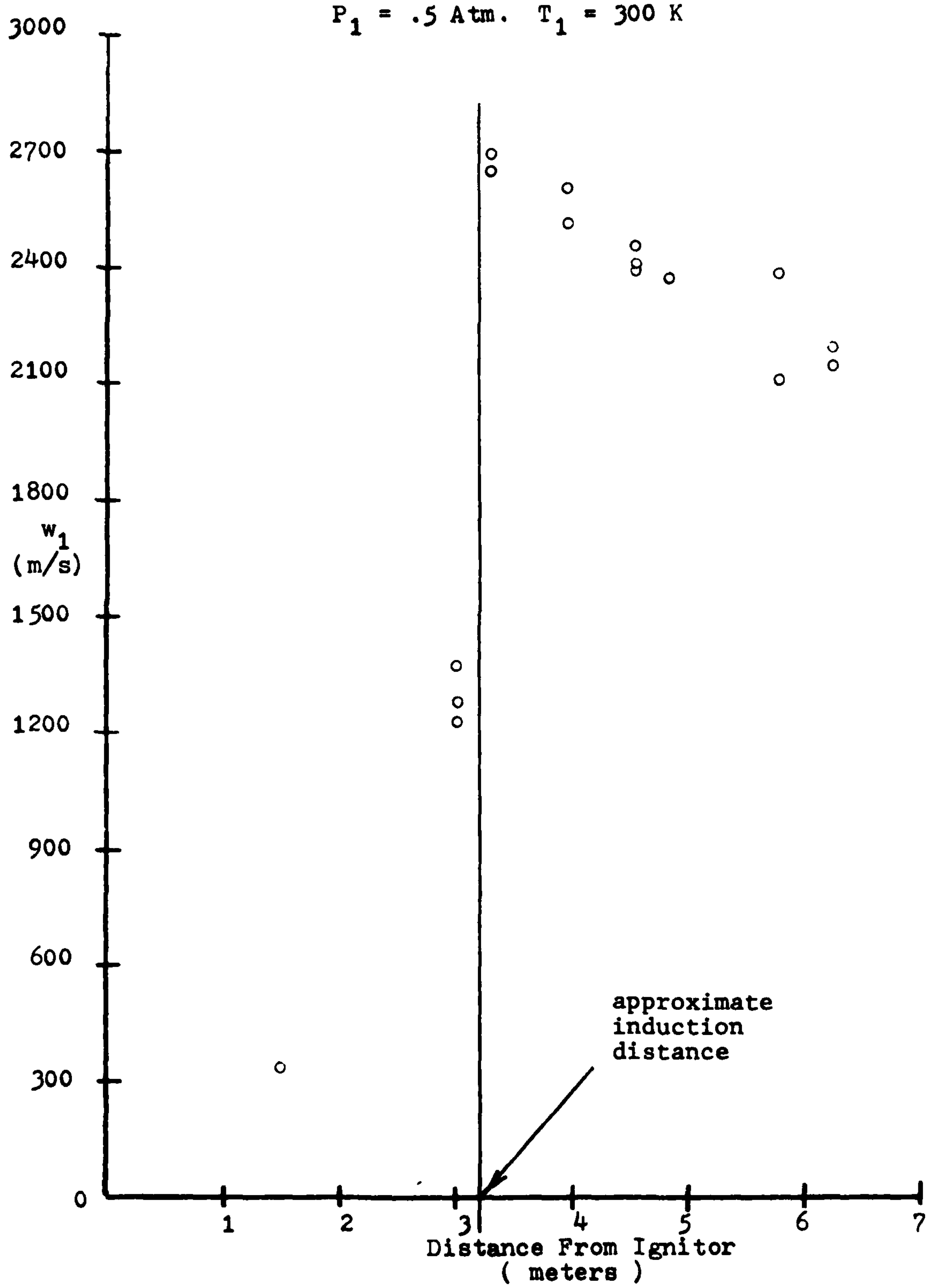
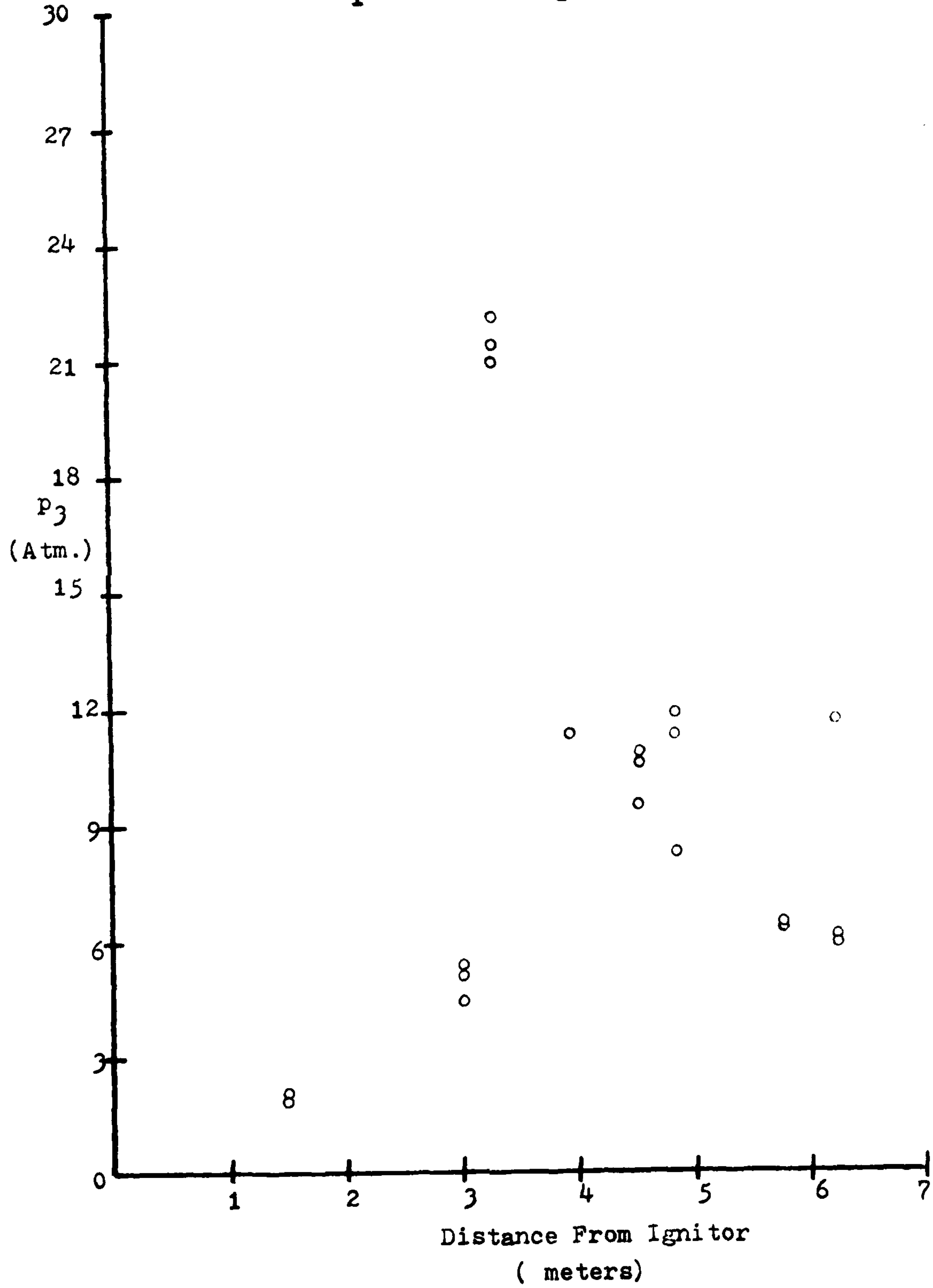


Figure 23
Wave Pressure Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + Ar$
$P_1 = .5$ Atm. $T_1 = 300$ K



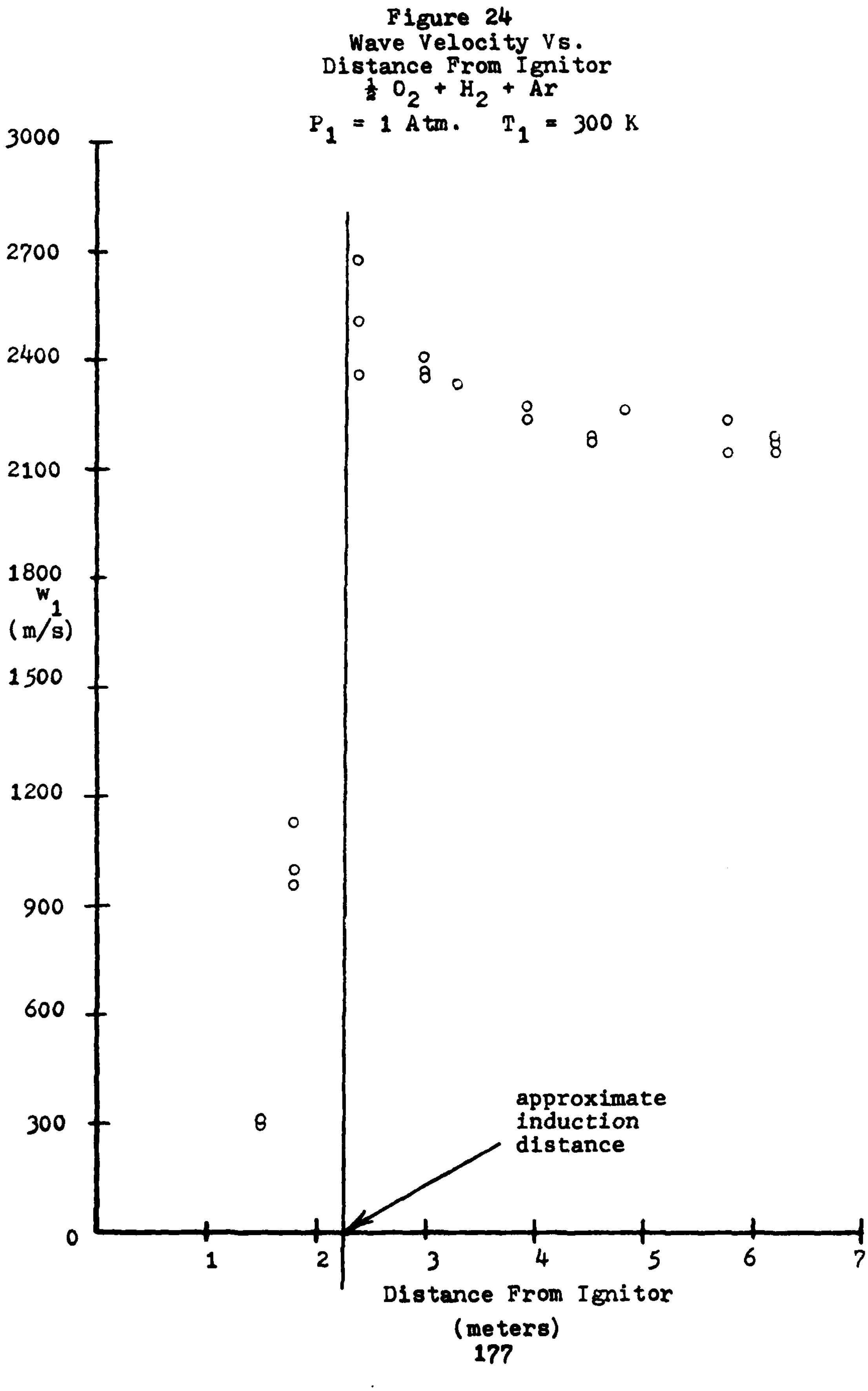


Figure 24
Wave Velocity Vs.
Distance From Ignitor
½ O2 + H2 + Ar
P1 = 1 Atm. T1 = 300 K
3000
2700
2400
2100
1800
w1
(m/s)
1500
1200
900
600
300
0
1
2
3
4
5
6
7
approximate
induction
distance
Distance From Ignitor
(meters)

Figure 25
Wave Pressure Vs.
Distance From Ignitor
$\frac{1}{2} O_2 + H_2 + Ar$
$P_1 = 1$ Atm. $T_1 = 300$ K

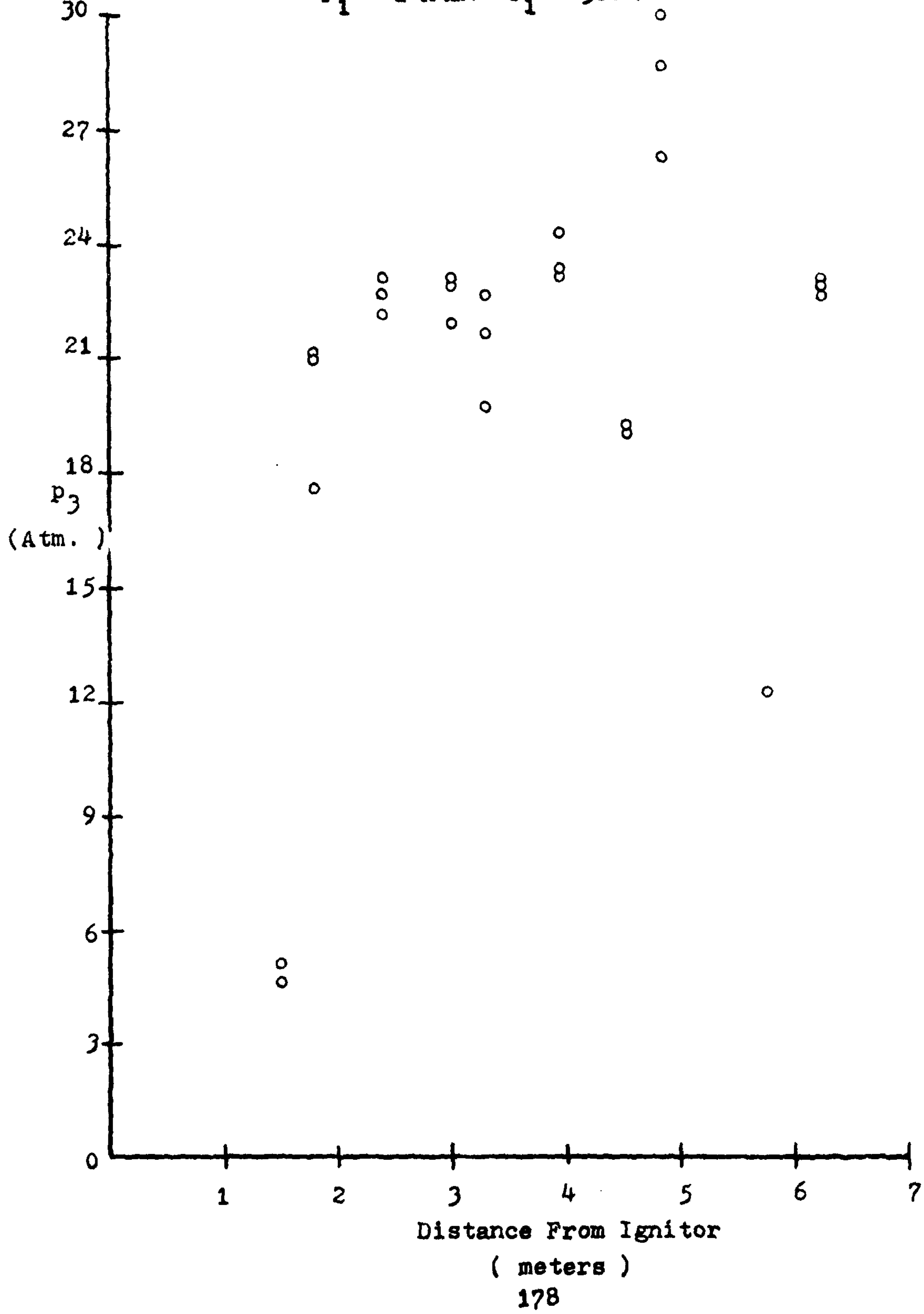


Figure 26

Wave Velocity Vs.
Distance From Ignitor
$\frac{1}{2}\,O_2 + H_2 + Ar$
$P_1 = 2$ Atm. $T_1 = 300$ K

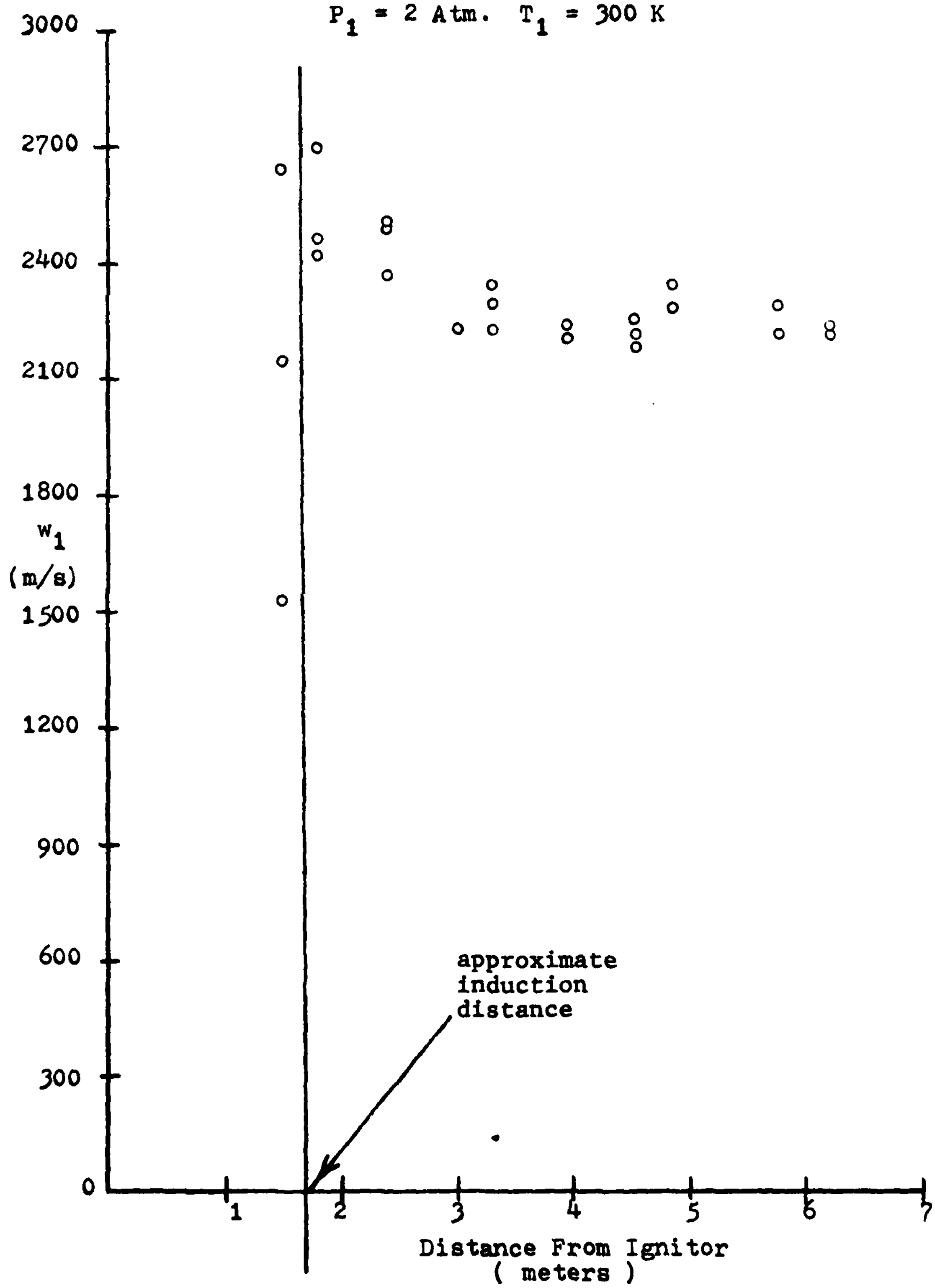
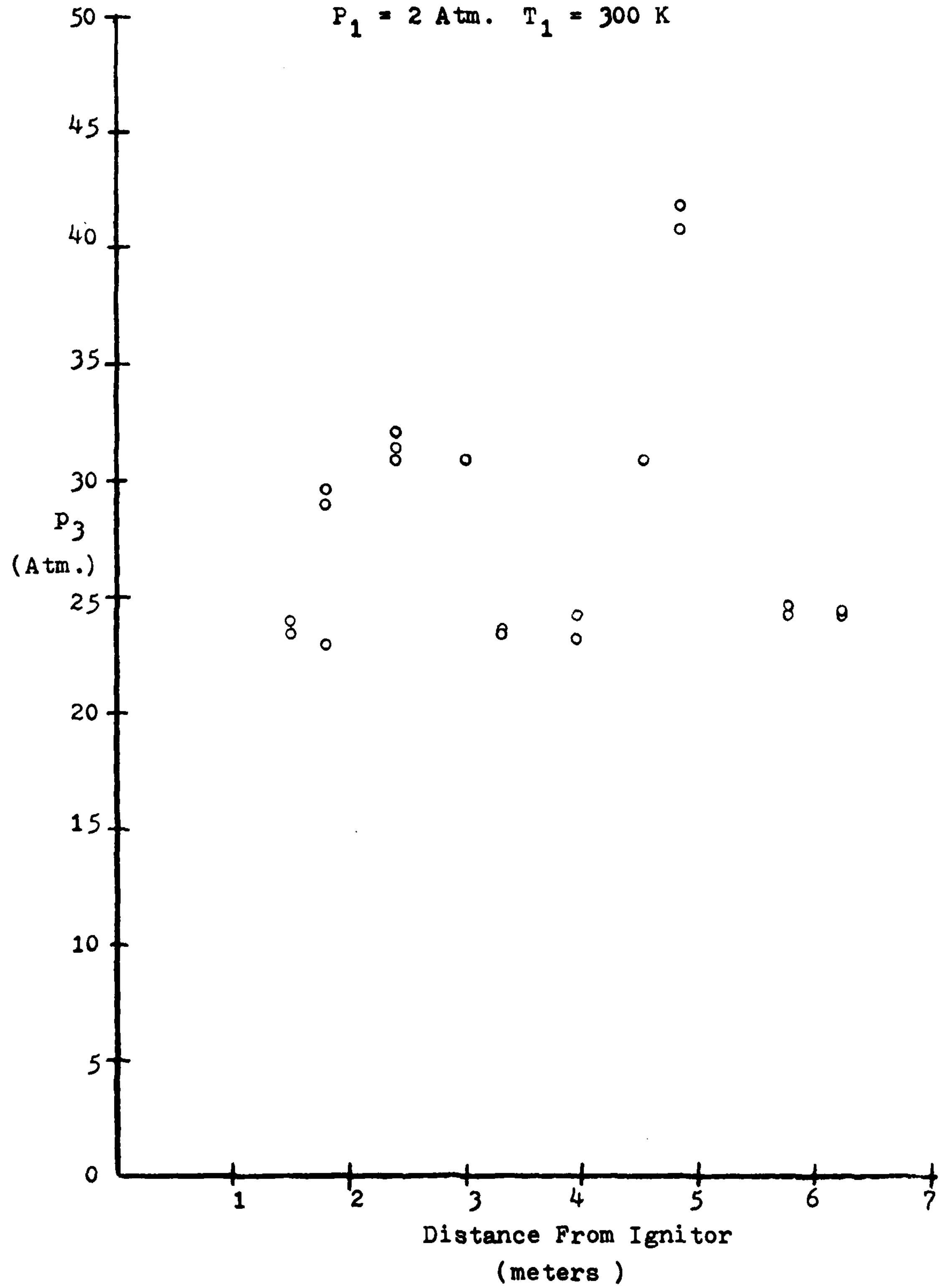
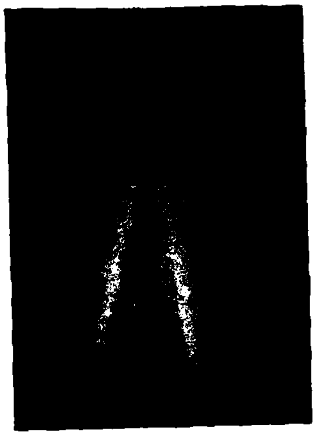


Figure 27
Wave Pressure Vs.
Distance From Ignitor

$\frac{1}{2}\ O_2 + H_2 + Ar$

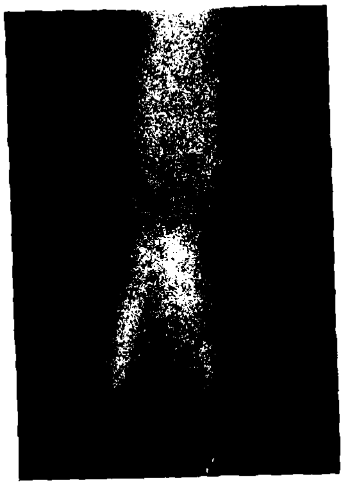
$P_1 = 2$ Atm. $T_1 = 300$ K



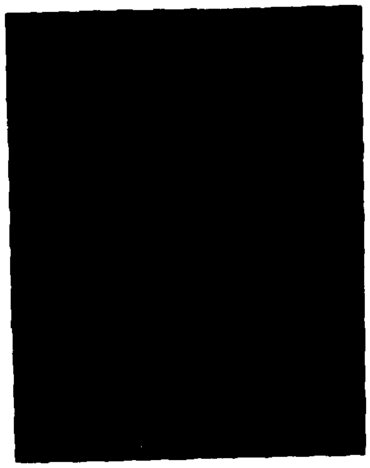


Initial Temp.= 0° C

Initial Temp.= Room



Initial Temp.= -50 to -100° C



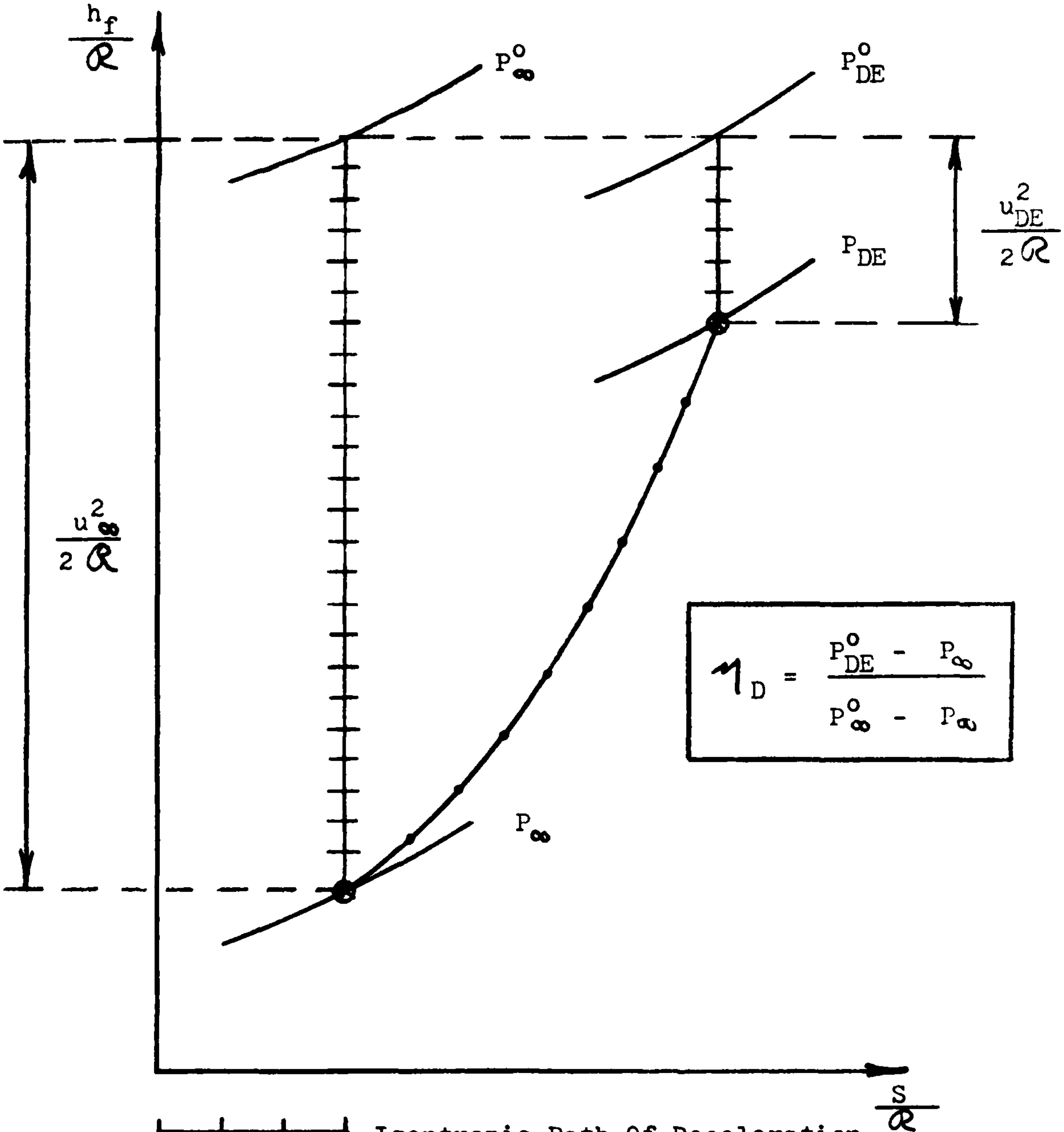
Initial Temp.= -100 to - 150 °C

Figure 28

Flame Photographs
30 % Hydrogen In Air

Flow Speed = 225 cc/s

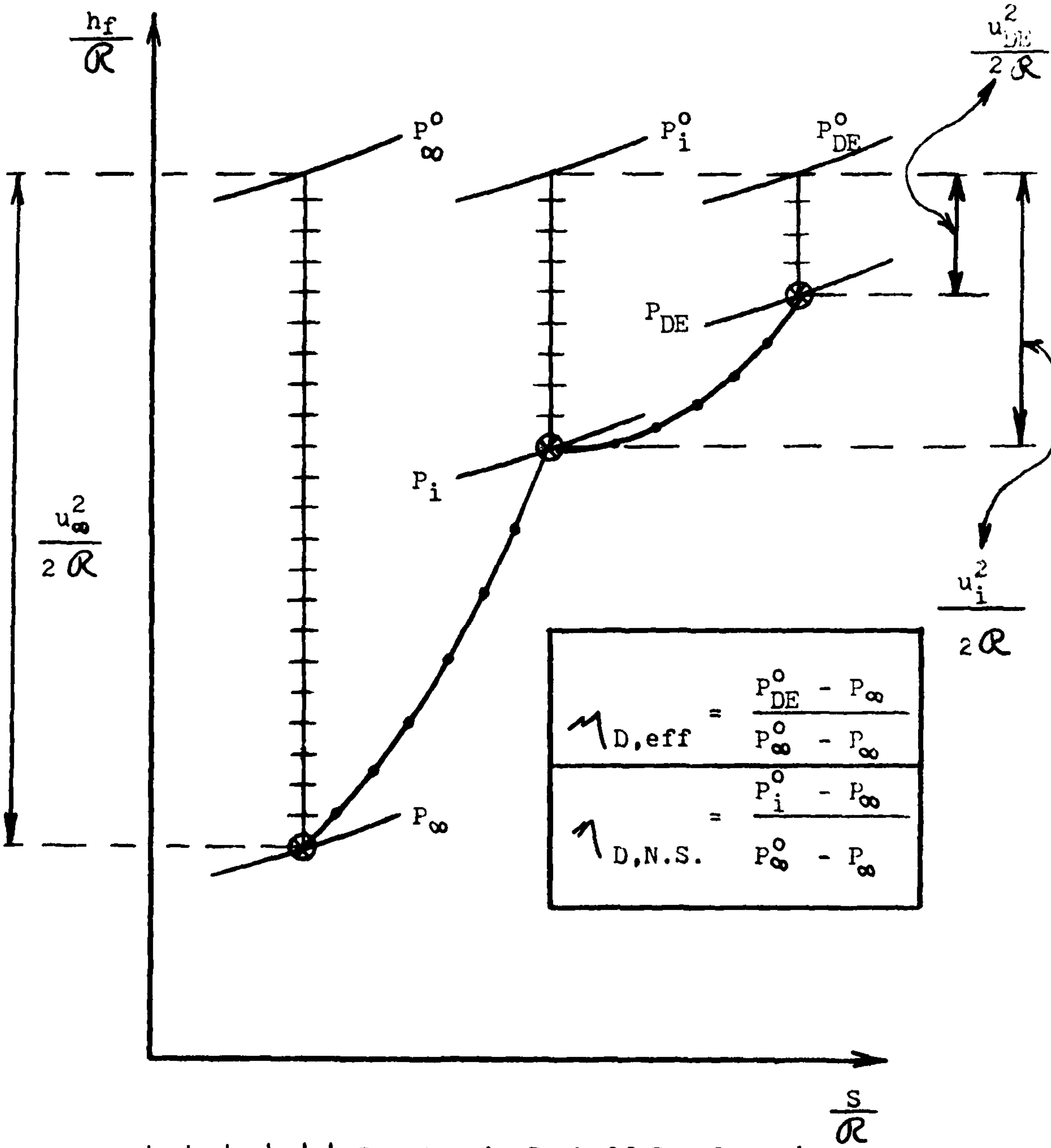
Figure 29a
Entropy - Enthalpy Diagram
Of A Ramjet Diffuser
With Shock - Free Inlet



Isentropic Path Of Deceleration

Actual Path Of Deceleration (Only ⊗ Points are known; the others are arbitrary)

Figure 29b
Entropy - Enthalpy Diagram
Of A Ramjet Diffuser
With Normal Shock At Inlet



Isentropic Path Of Deceleration

Actual Path Of Deceleration (Only ⊗ Points are known; the others are arbitrary)

Figure 30a

p_3/p_1 Vs. T_1 For

$1/2\ O_2 + H_2 + 1/2\ CO_2$

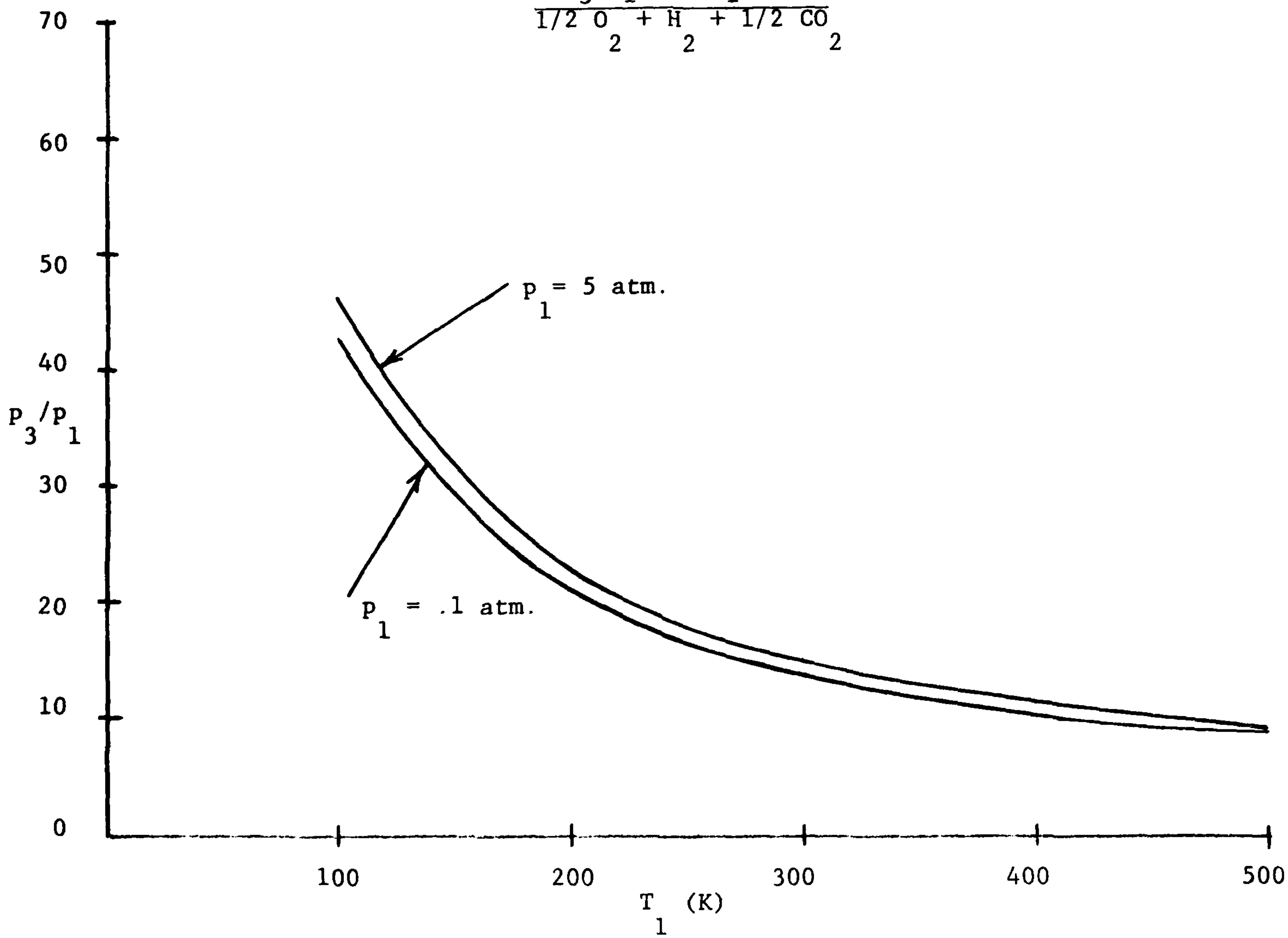


Figure 30b

p_3/p_1 Vs. T_1 For

$1/2\ O_2 + H_2 + N_2$

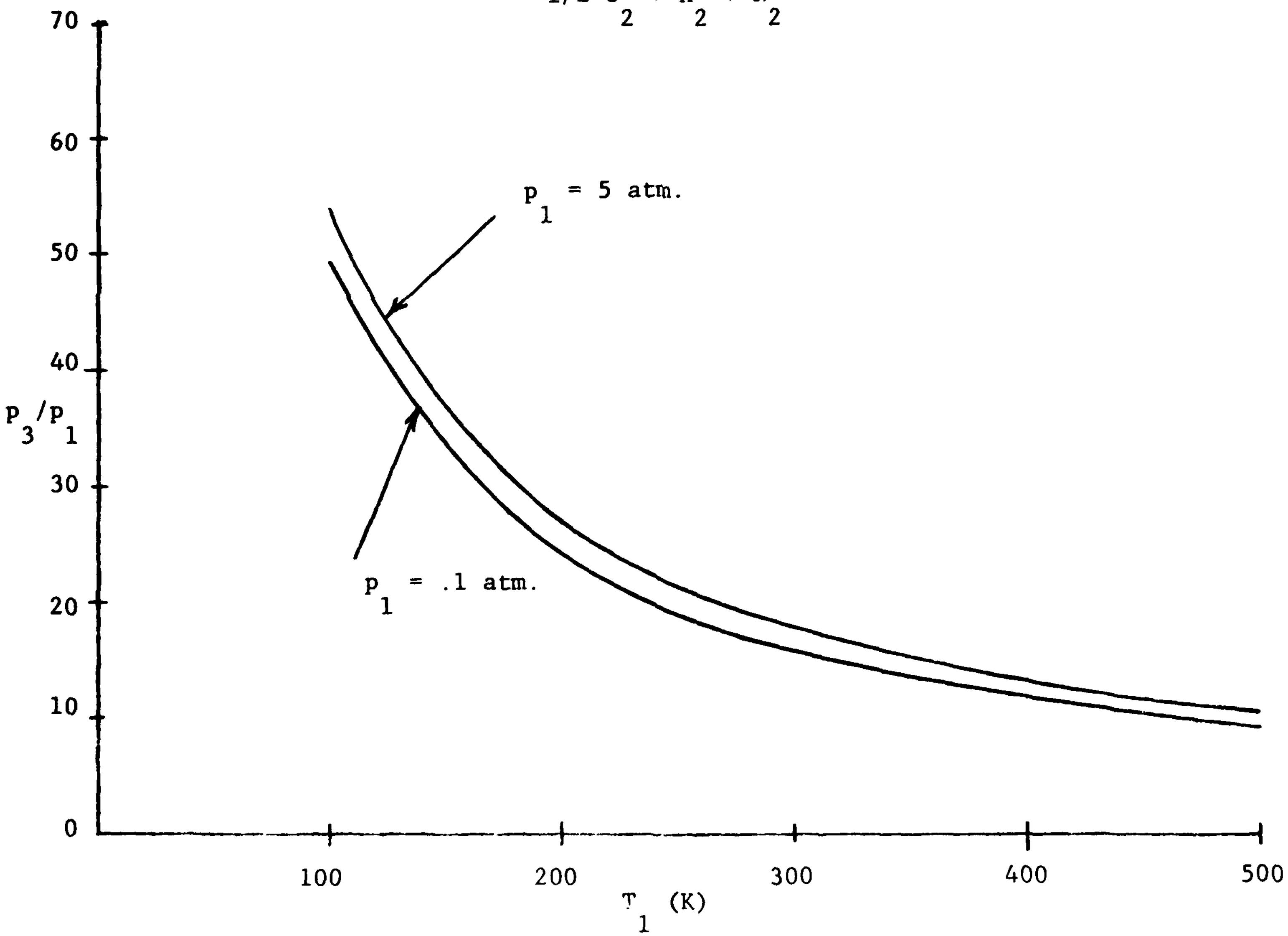


Figure 30c

p_3/p_1 Vs. T_1 For $1/2\ O_2 + H_2 + He$

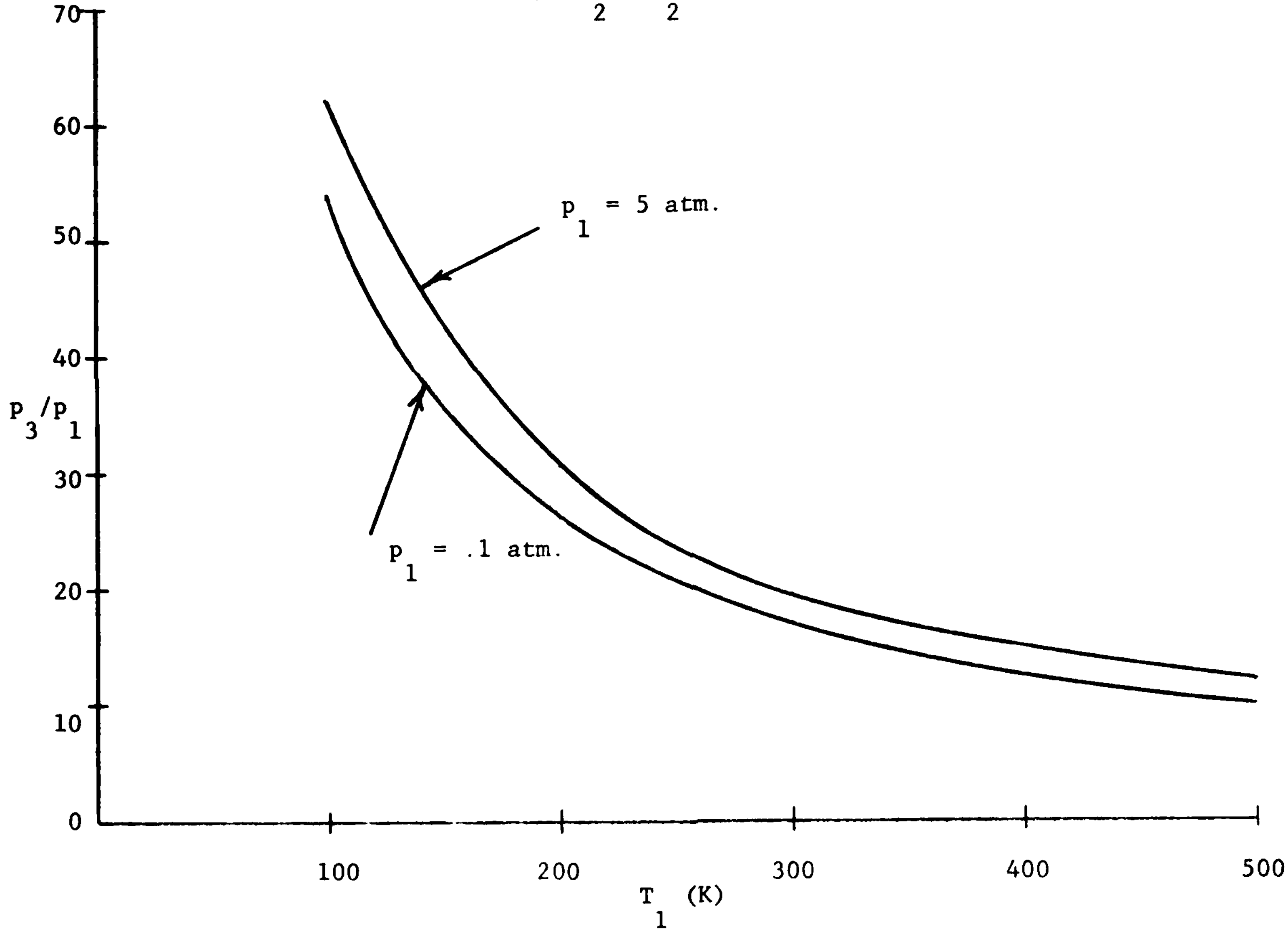


Figure 30d

p_3/p_1 Vs. T_1 For

$1/2\ O_2 + H_2 + Ar$

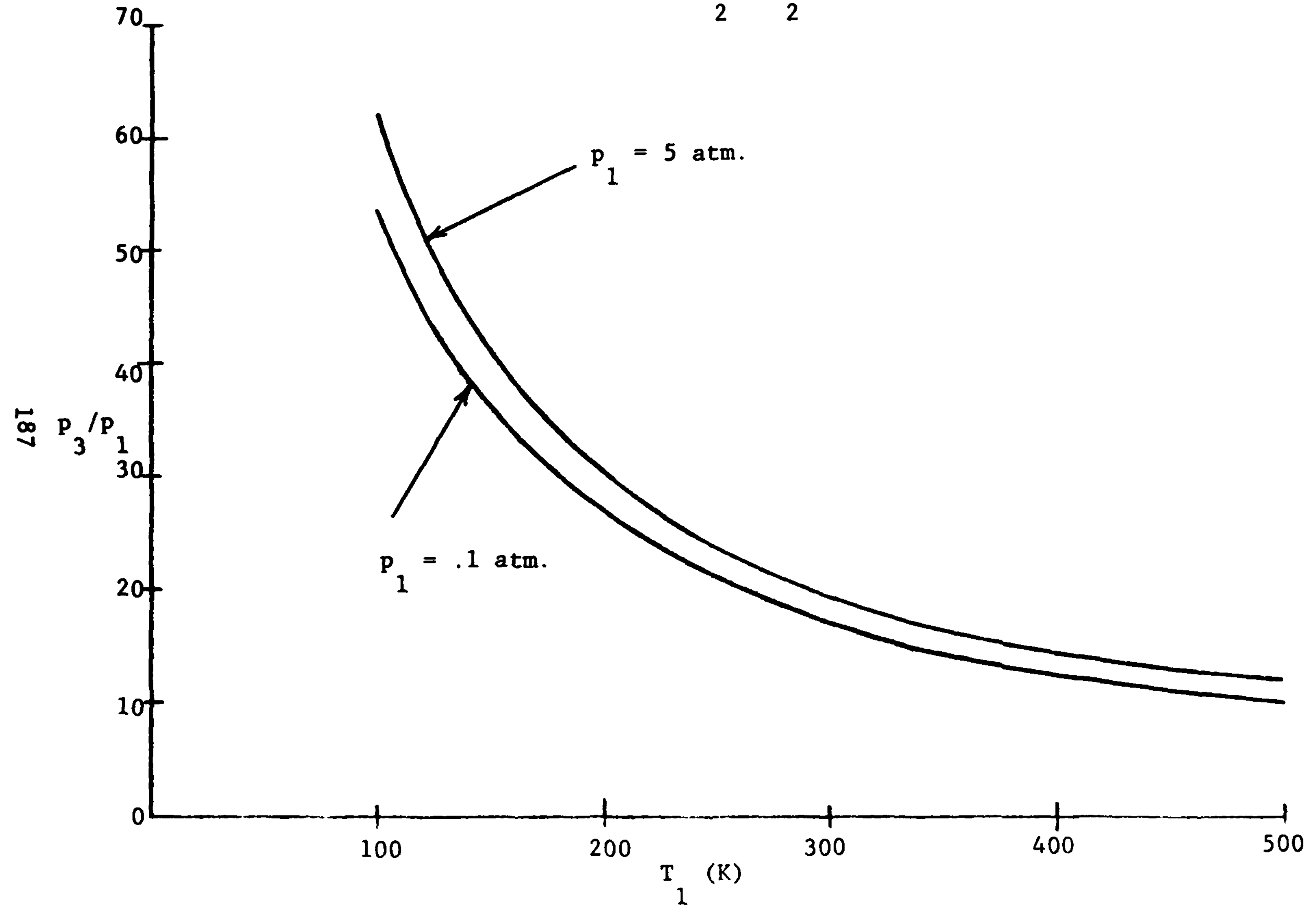
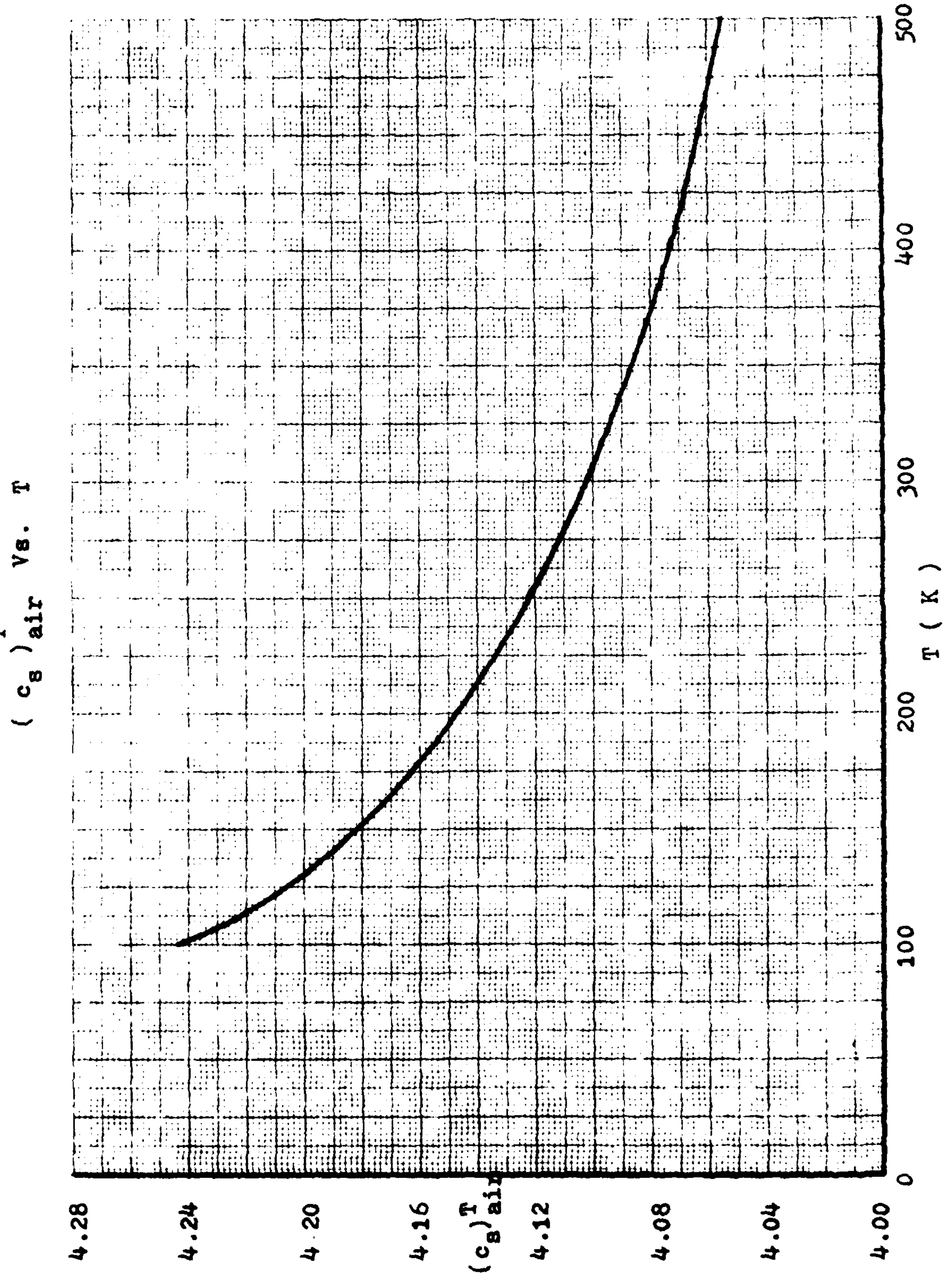
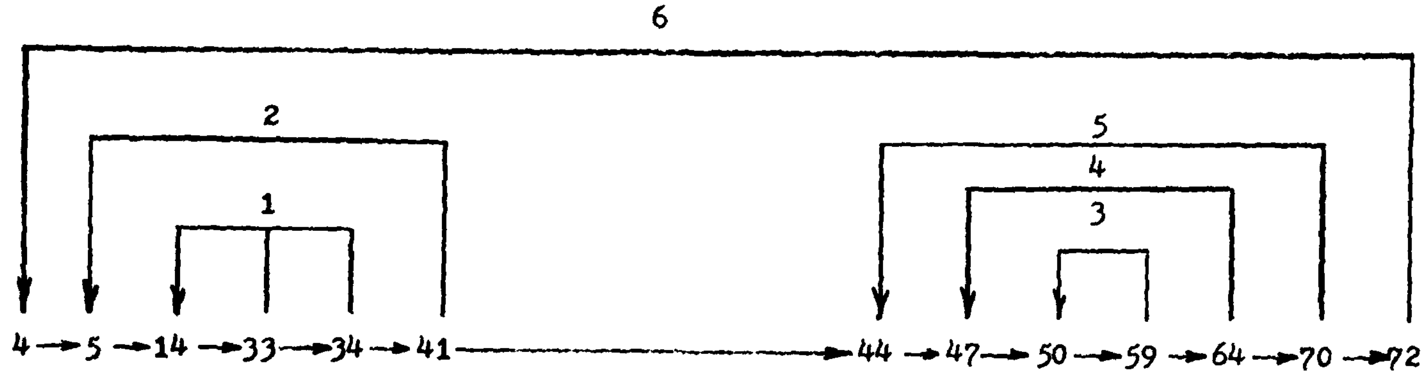


Figure 31



(c_s)^T_air Vs. T
T (K)
(c_s)^T_air
0
100
200
300
400
500
4.28
4.24
4.20
4.16
4.12
4.08
4.04
4.00

Ramjet Combustion Chamber Iteration With M_c Specified



loop 1: The composition of the combustion gas is calculated by means of the condition that:

$$f_{O_2}^{calc} = f_{O_2} \quad \text{and} \quad f_{N_2/O_2}^{calc} = 3.76$$

loop 2: T_c is obtained from the condition that $\left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^{o\ calc}} = \left(\frac{h_f}{\mathcal{R}}\right)_{CG}^{T_c^o}$

loop 3: The composition of the dissociated air at the diffuser exit is obtained from the condition that:

$$f_{N_2}^{calc} = 3.76$$

loop 4: p_{DE} is obtained from the condition that $\left(\frac{s}{\mathcal{R}}\right)_{eq\ air}^{T_{DE}} = \left(\frac{s}{\mathcal{R}}\right)_{air}^{T_\infty} + \left(\frac{\Delta s}{\mathcal{R}}\right)$

loop 5: T_{DE} is obtained from the condition that $u_{DE}^{(E)} = u_{DE}^{(M-C)}$

loop 6: p_c is obtained from the condition that $A_c = A_{DE} + A_f$ and $p_c^{calc} = p_c^{est}$

The sequence of numbers from 4 to 72 refer to line numbers in the program.

Figure 32

Figure 33

Specific Thrust vs. Flight Mach No.

Altitude = 100 000 feet T_∞ = 233.1 K

η_c = .7

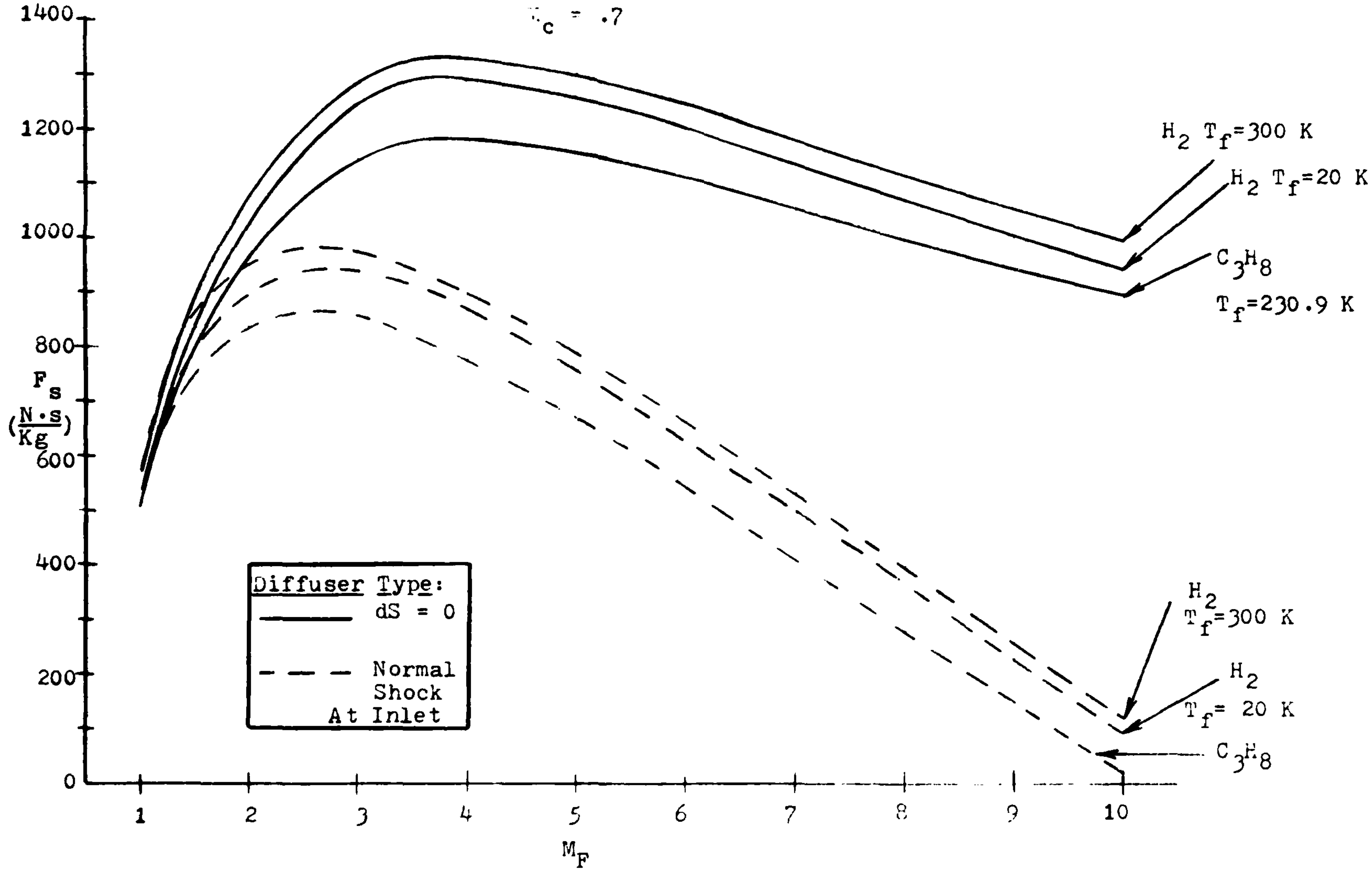


Figure 34
Thrust Specific Fuel Consumption
Vs. Flight Mach No.

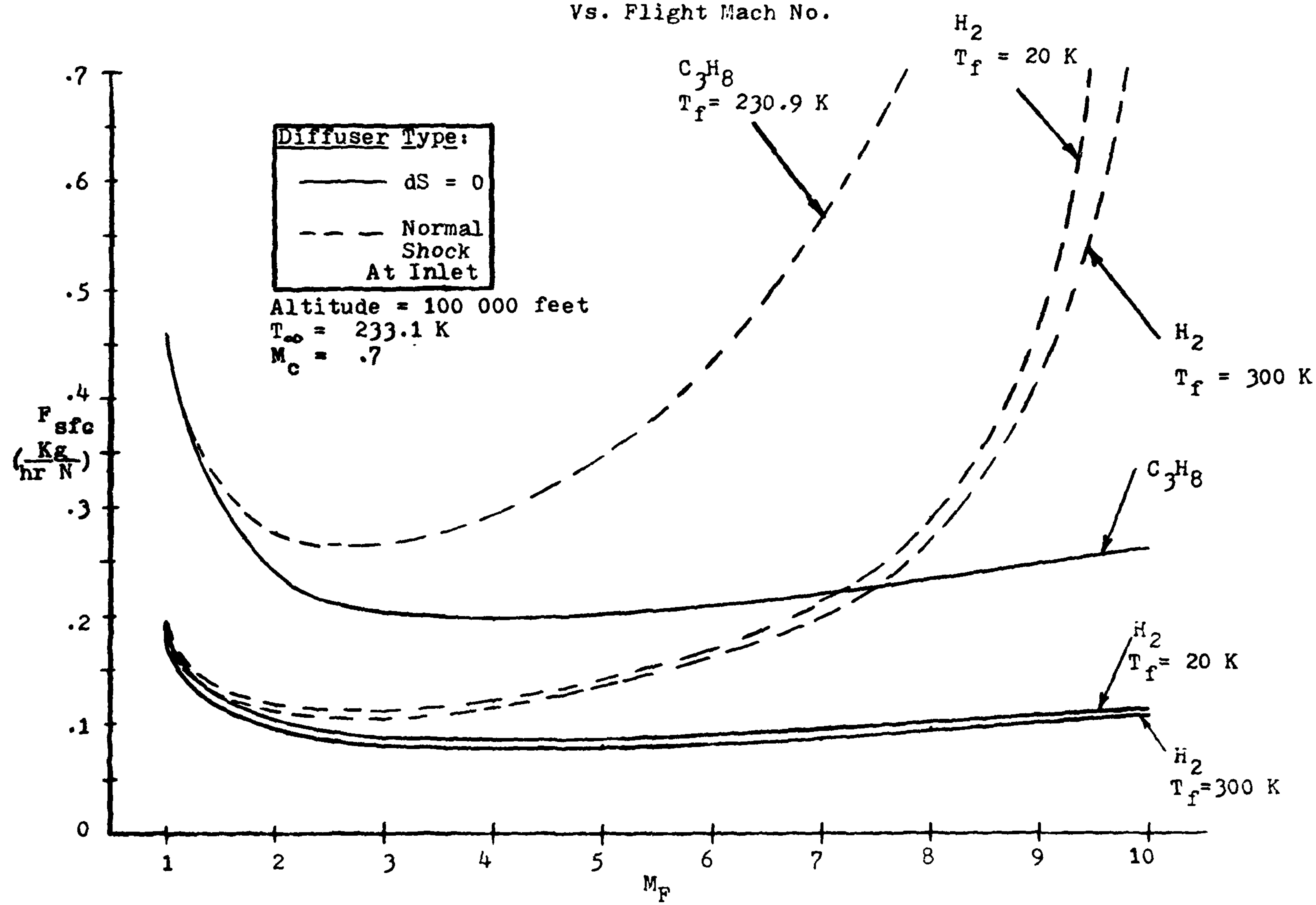


Figure 35
Thermodynamic Efficiency Vs. Flight Mach No.

Altitude = 100 000 feet T_∞ = 233.1 K
M_c = .7

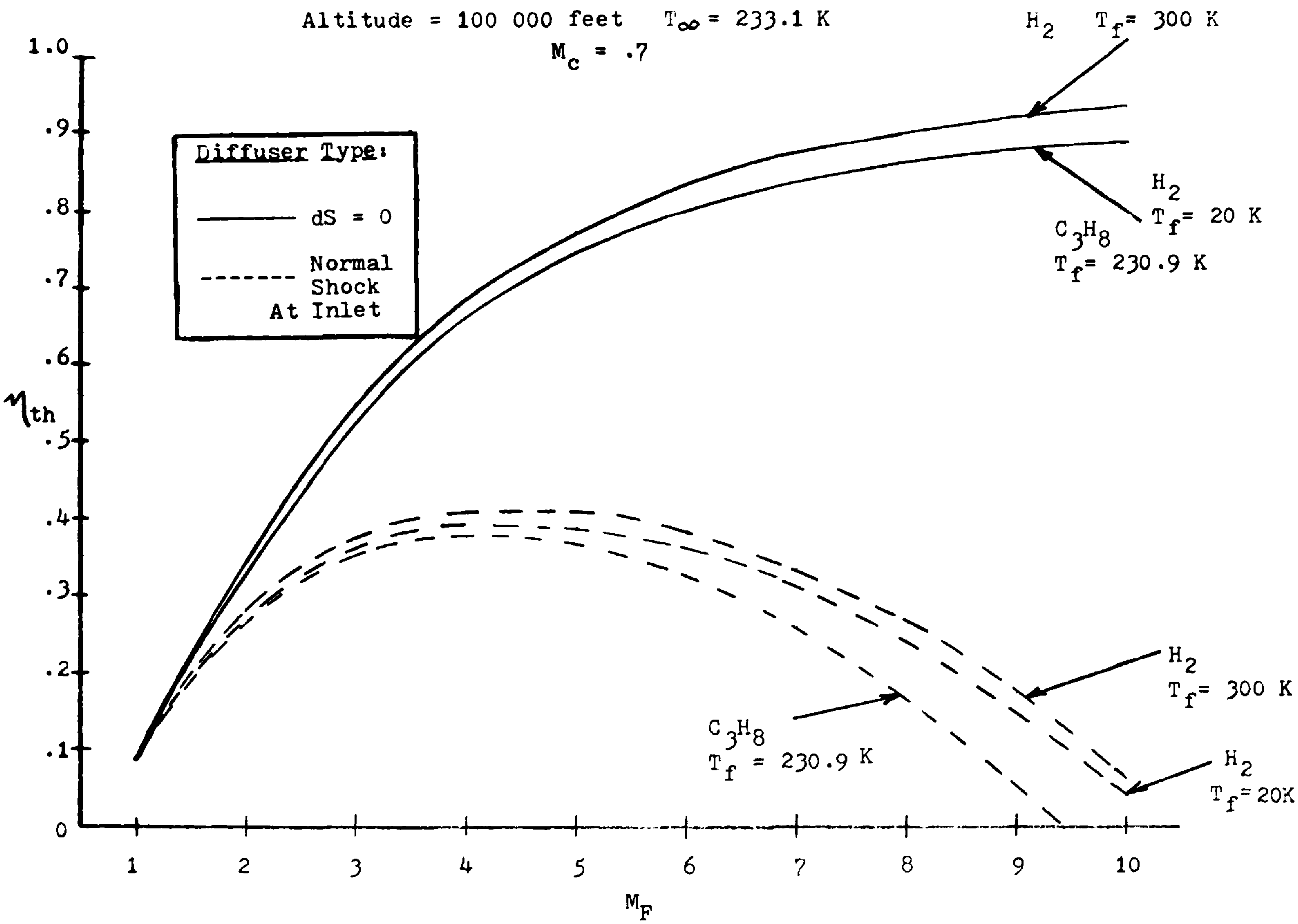


Figure 36

Overall Efficiency, η_o, Vs. Flight Mach No.

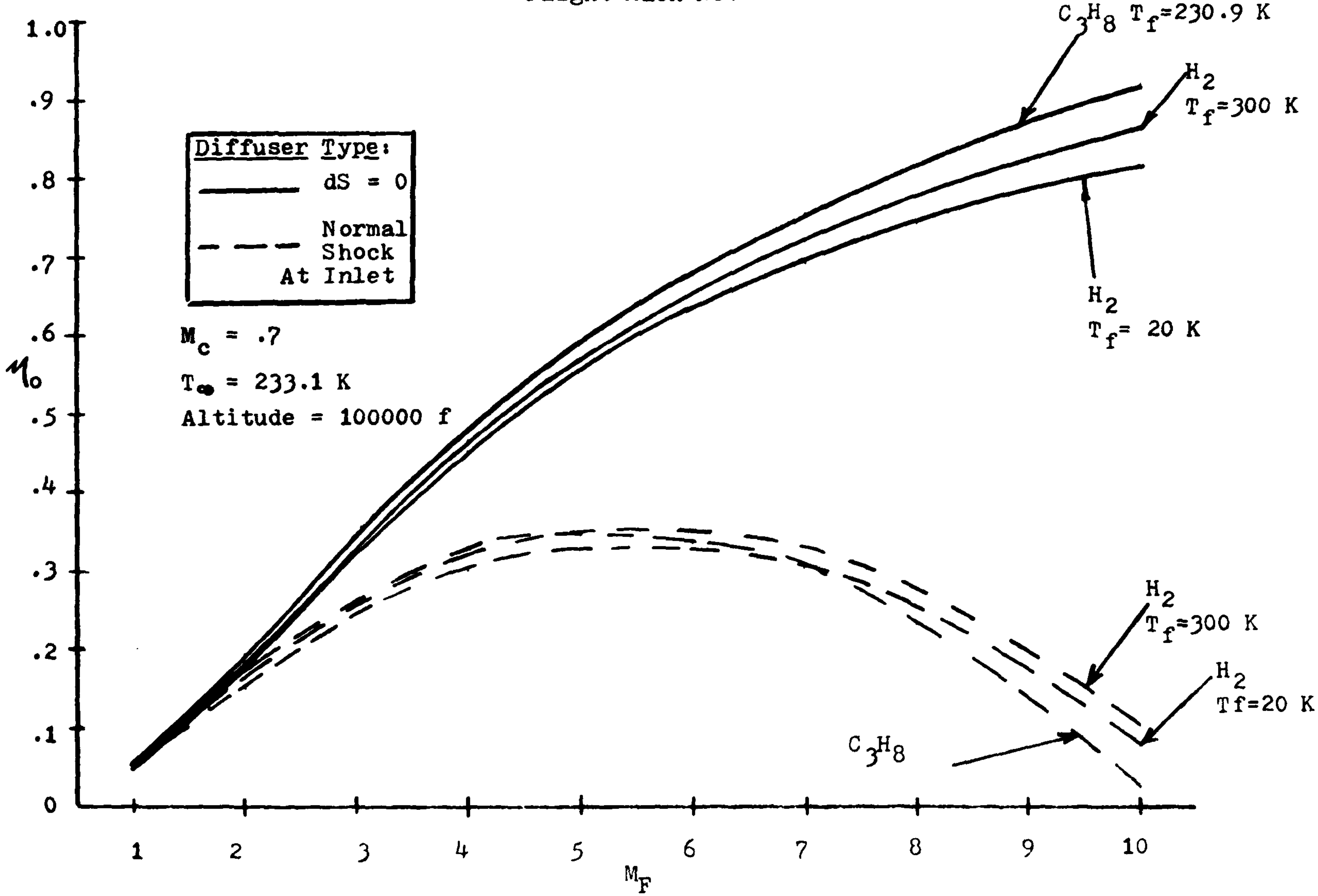


Figure 37
Specific Thrust Vs. Altitude
Ramjet With Isentropic Diffuser
$u_\infty = 1226.39$ m/s
$M_c = .7$

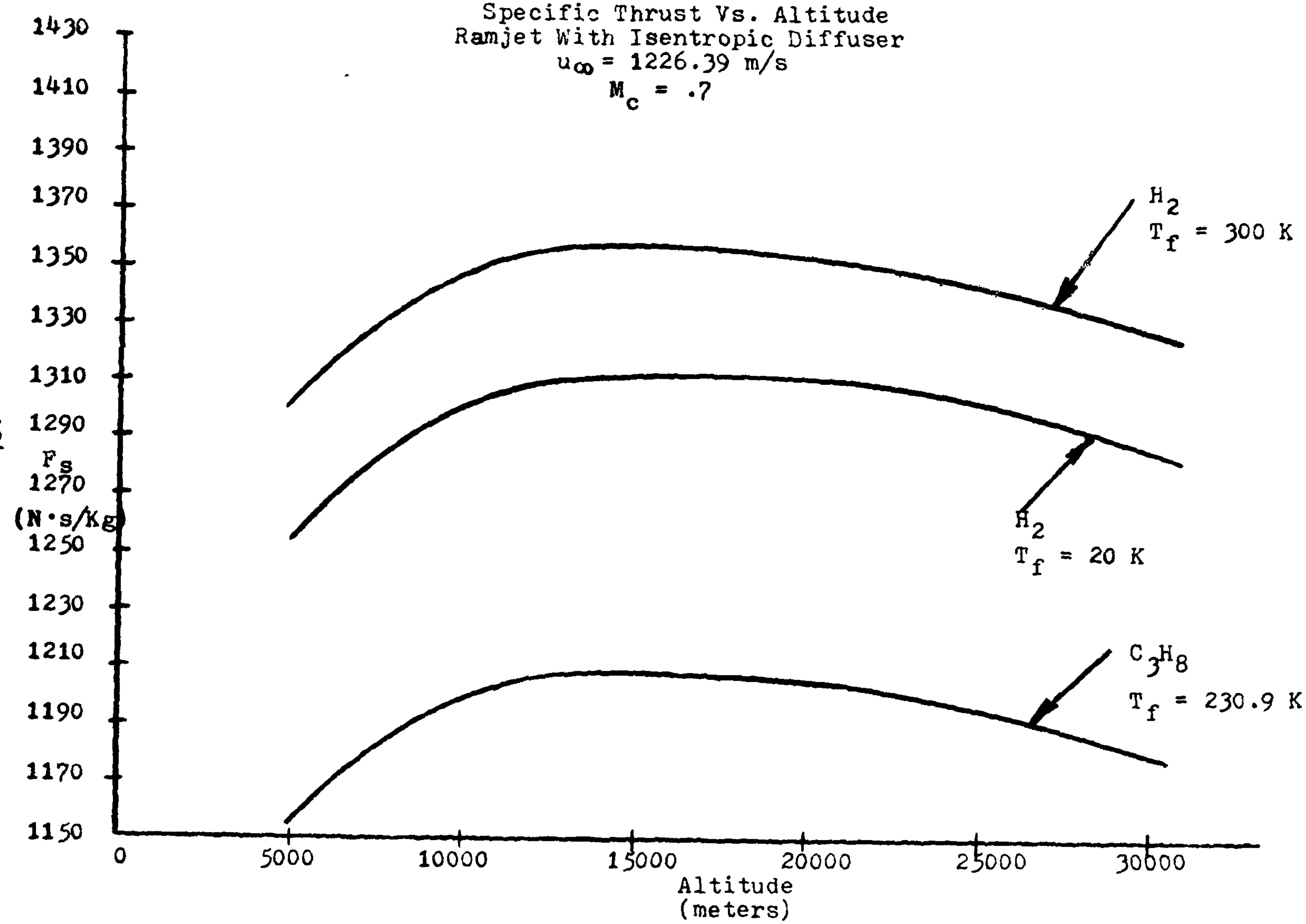
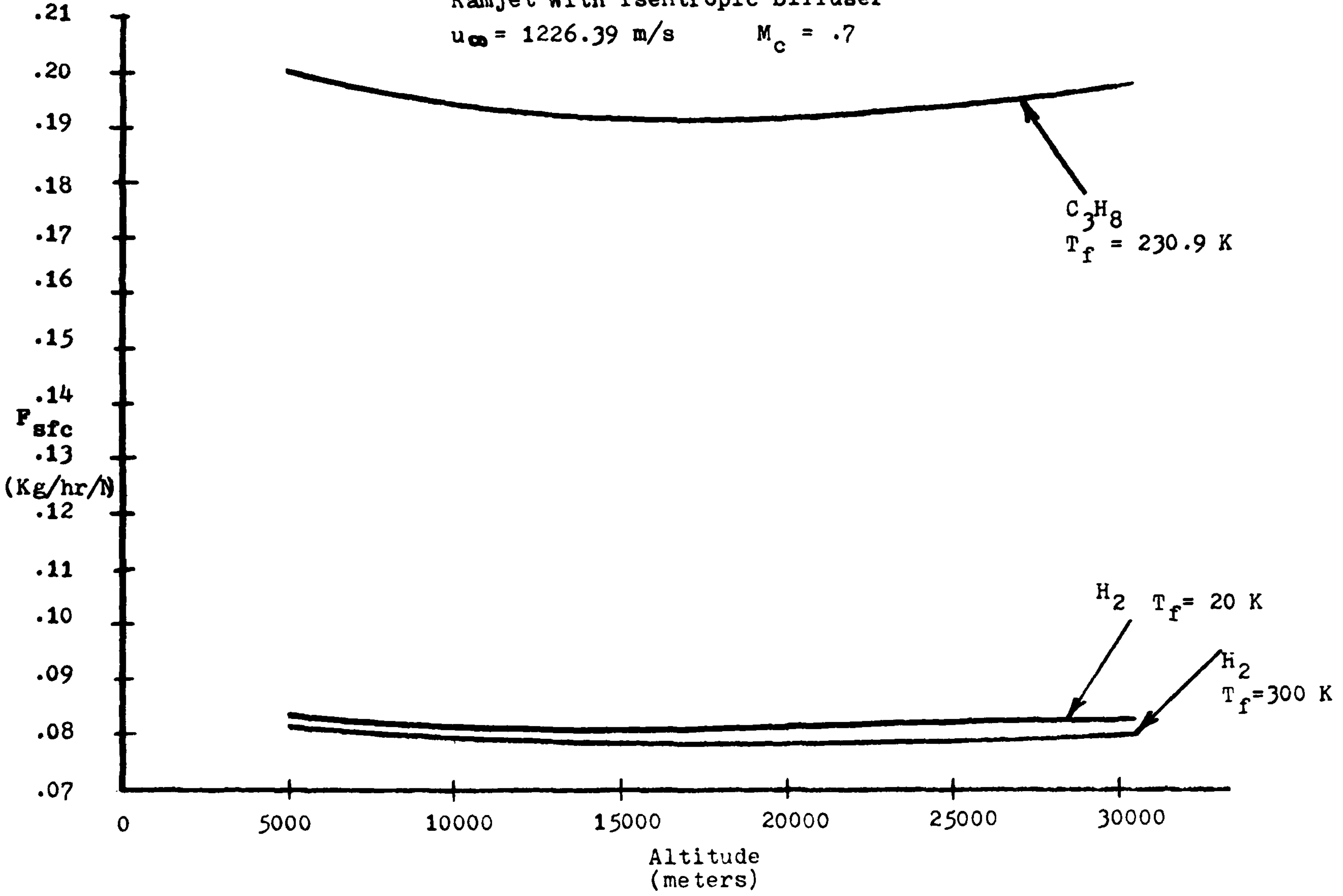


Figure 38
Thrust Specific Fuel Consumption
Vs. Altitude
Ramjet With Isentropic Diffuser
$u_\infty = 1226.39$ m/s $M_c = .7$



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